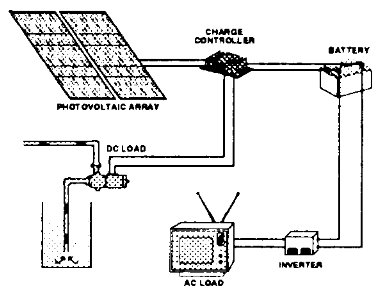
MAINTENANCE AND OPERATION OF STAND-ALONE PHOTOVOLTAIC SYSTEMS

Naval Facilities Engineering Command, Southern Division
Photovoltaics Review Committee, Department of Defense
and Sandia Nat'l Laboratories' Design Assistance Center



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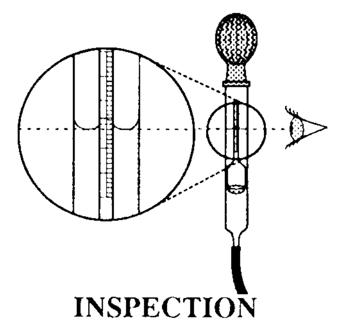

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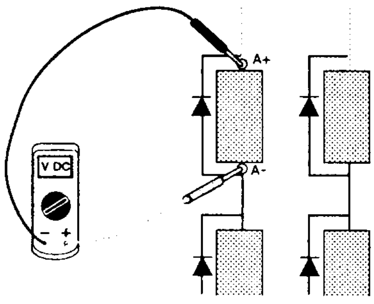

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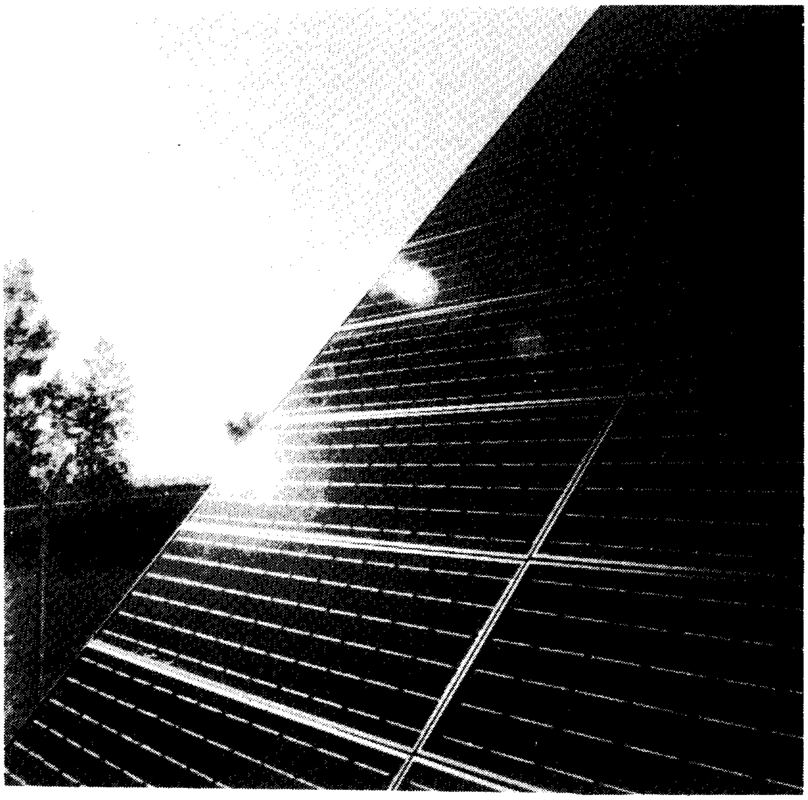

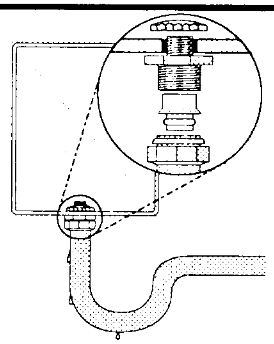

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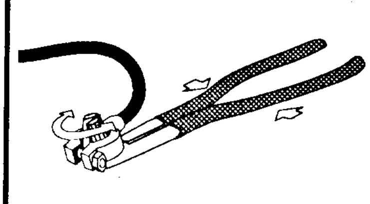

MAINTENANCE

Architectural Energy Corporation

December 1991

Sandia National Laboratories - a U.S. Department of Energy Multiprogram National Laboratory

PHOTOVOLTAIC SYSTEMS ASSISTANCE CENTER
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ABSTRACT

This manual is a guide for engineers, planners, maintenance supervisors, and all maintenance personnel involved in the operation, inspection, troubleshooting, repair, and maintenance of photovoltaic (solar electric) systems. The manual is designed to be used in the field by the personnel performing the actual inspection, maintenance, or repair of solar power systems.

ACKNOWLEDGMENTS

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PREFACE

This document was prepared for the U.S. Department of Defense (DOD) Photovoltaics Review Committee as part of its efforts to inform military personnel of the attributes of photovoltaics (PV) for military applications. The intended audience for this manual is engineers, planners, maintenance supervisors, and all maintenance personnel involved in the operation, inspection, troubleshooting, repair, and maintenance of stand-alone photovoltaics systems. The manual is designed to be used in the field by the personnel performing the actual inspection, maintenance, or repair of solar power systems.

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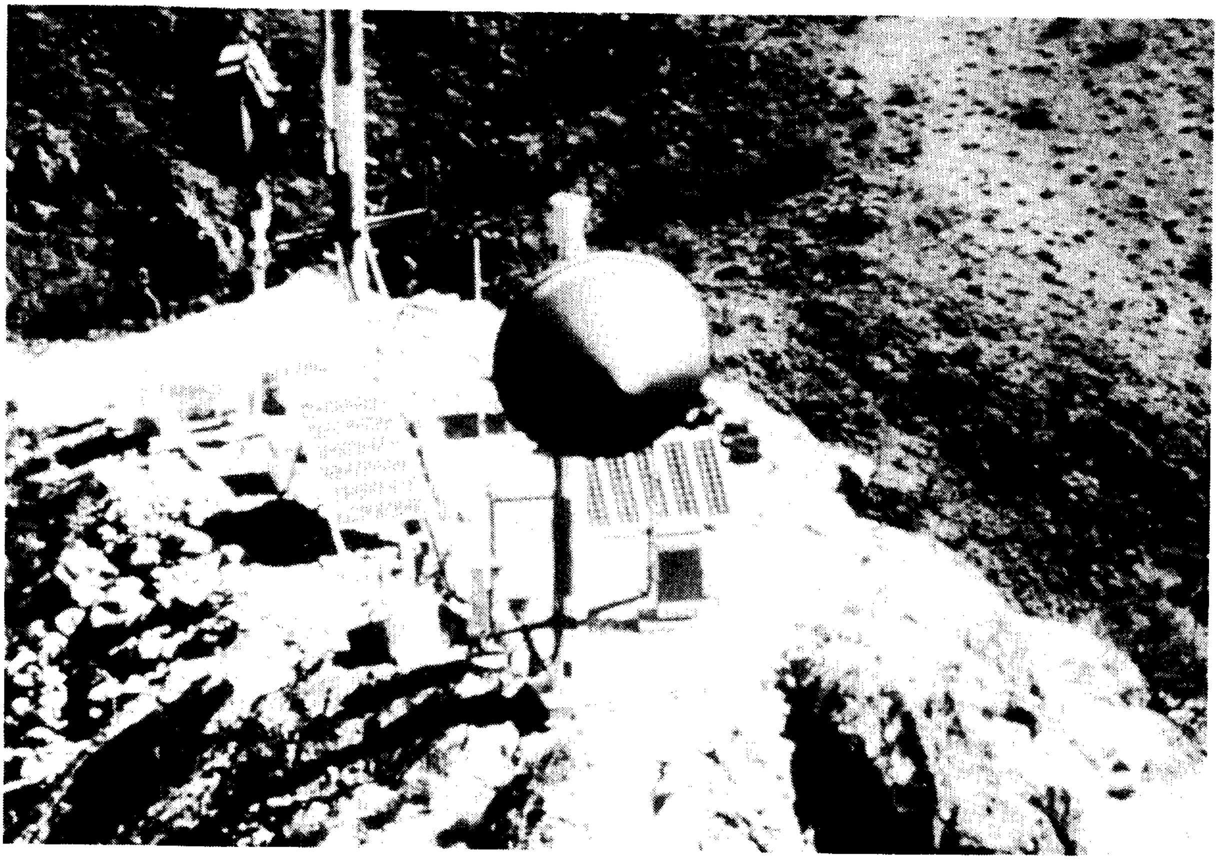

Communications Repeater Station
White's Peak
Yuma Proving Grounds, Arizona

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1.0 INTRODUCTION

What You Will Find In This Chapter

This chapter presents the purpose, scope, and structure of the manual. Recommended ways to use the manual are described.

Please read this chapter carefully; it will enable you to effectively use this manual in solar electric system operation, inspection, troubleshooting, repair, and maintenance activities.

1.1 PURPOSE OF THIS MANUAL

This manual provides information on the operation, inspection, troubleshooting, repair, and maintenance of solar electric systems.

Solar electric systems are sometimes called photovoltaic systems. The word "photovoltaic" can be abbreviated to "PV." Photovoltaic systems independently convert the sun's light into electricity. This electricity can be used directly, stored in batteries, or fed into an electric utility's grid system.

We assume the reader is working with an existing system, and wants to know how it works or how to maintain and repair it. We also assume the reader is a journeyman or master electrician or has a level of experience and knowledge equivalent to that of a journeyman.

An effort has been made to have the procedures and practices discussed in this manual comply with the National Electric Code (NEC). The reader should be aware, however, that many existing systems were installed before any attempt at defining this compliance was initiated. This is especially true for the small, stand-alone PV systems for which this manual is intended. The reader should be careful not to assume, therefore, that an unfamiliar system is in compliance, and should observe all safety precautions as if it were not. If inconsistencies are found, the service person should correct them if possible. For more detailed information on the NEC and how it applies to PV systems, refer to *Photovoltaic Power Systems and the National Electric Code: Recommended Installation Practices,* DOE document DE-A04-90AL57510, prepared by Southwest Region Experiment Station, Southwest Technology Development Institute of New Mexico State University.

NOTE

This manual is designed to be used in the field by the personnel performing work on photovoltaic systems. It should be in a service vehicle, not a bookcase!

1.2 SCOPE OF THIS MANUAL

The manual covers service issues for stand-alone photovoltaic systems with fixed, variable-tilt, and tracking arrays. Design and installation techniques are not included, except where they are involved directly with service activities.

Photovoltaic cells, modules, and arrays, as well as balance of system components such as batteries, voltage regulators, inverters, and associated wiring, are included. Individual loads are not examined, but different categories of loads are covered. These categories are defined by the influence they have on the photovoltaic system.

Systems connected to an electric utility's lines, called "grid-connected," are not discussed in this manual. Systems using a backup mechanical electric generator, known as "hybrid" systems, are not specifically discussed, although the photovoltaic system components are the same.

In addition to information about general types of equipment, information specific to particular manufacturers' equipment is given when necessary.

Chapters of this manual are:

Chapter 2 - Operation
Chapter 3 - Inspection
Chapter 4 - Troubleshooting
Chapter 5 - Repair
Chapter 6 - Maintenance

1.3 HOW TO USE THIS MANUAL

1.3.1 Review of Manual Structure. You will be asked to flip back and forth through the manual to familiarize yourself with the location of the different sections.

Take time to actually look at the pages being described. A good understanding of the structure of the manual will make it more useful to you.

1.3.2 User Alternatives. Ideally, you should read the entire manual before beginning work on a photovoltaic system. If this is not possible, read Chapter 2, Operation, and the appropriate chapter for the work you will be performing.

1.3.3 First Page of Each Chapter. The first page of every chapter describes what is, and what is not, in that chapter. In some cases it will tell you where to find other useful information.

Many chapter introductions include information you may need to understand the rest of the chapter. Therefore, we suggest you read the chapter introduction before reading other parts of the chapter.

Take a moment now to read the first page of each chapter.

1.3.4 Record Sheets. Most chapters end with some type of record sheet. They are designed to be copied and used for the photovoltaic system being serviced.

The sheets can be "customized" for your particular needs and preferences. If they are not appropriate for the specific system under service, modify the worksheet to meet your needs.

It is recommended that the completed record sheets be three-hole punched and inserted into a loose-leaf notebook. The notebook becomes a permanent service history of that particular photovoltaic system.

Take a look at the inspection record sheet at the end of Chapter 3.

1.3.5 Self-Study Questions. At the end of each chapter, questions for self-study are printed. The answers to the questions appear at the end of the manual in Appendix D.

The questions can be used to confirm your understanding of the material in the chapter, or as part of a formal training program.

1.3.6 Appendices. The manual contains four appendices. Tool, supply, and spare parts lists are contained in Appendix A. You should scan these Appendices to learn what types of information they contain, and use them as a reference when needed.

1.3.7 Notes, Cautions, and Warnings. Boxes containing notes, cautions, and warnings appear throughout the manual. Their purpose is to alert you to an important aspect of the topic being discussed. NOTES provide helpful information that does not otherwise fit into the text. This is an example of a note:

NOTE
These screws are the same size as the ones used on the lower part of the frame.

CAUTIONS draw attention to the possibility of equipment damage if the instructions are not followed. As an example:

CAUTION!
If the screw is tightened too far, the case can be cracked.

WARNINGS draw attention to the possibility of personal injury if the instructions are not followed. An example of a warning is:

WARNING!
Be sure to turn off the electric power supply before removing the voltage lead. Electrocution is possible otherwise.

1.3.8 Chapter and Page Format. A three-point system is used on every page to let you know where you are in the manual. First, a footer at the bottom "outside" of every page shows the chapter title. On this page it is "INTRODUCTION."

The second point is a footer below the chapter title with the section number and title. For example, "1.3 HOW TO USE THIS MANUAL" on this page.

Finally, page numbers, continuous throughout the manual, are at the bottom center of every page.

Smaller illustrations are placed on the same page as corresponding text. Full-page illustrations are on an adjacent page, with caption to the side of the illustration. The same three-point orientation system is used on full-page illustrations.

1.3.9 Figures and Tables. Figures and tables are numbered consecutively through each chapter, with the chapter number as a prefix. For example, the figures in Chapter 2 are numbered 2-1, 2-2, 2-3, and so on.

After the table of contents, a list of figures and a list of tables is supplied for your convenience.

2.0 OPERATION

What You Will Find In This Chapter:

This chapter describes the different types of photovoltaic systems, how they work, what components make up the systems, and how those components work.

It is strongly suggested you read this chapter before starting work on a photovoltaic system or before reading other sections of this manual.

This chapter does not contain many of the cautions and warnings about specific components and operations that other chapters do. Read the appropriate chapters for specific operations as well as this one.

2.1 PHOTOVOLTAIC ELECTRICITY

2.1.1 Introduction. This section describes the similarities and differences between photovoltaic and "conventional" AC (Alternating Current) electricity. Knowing this information will help you to better understand the systems and the service operations.

For this section, you need to know that a photovoltaic module is the smallest unit of solar electricity-producing equipment you will normally work on. A photovoltaic array is a group of one or more modules.

2.1.2 Impact of Load. The amount of electricity produced by a photovoltaic system to operate lights, motors, electronics, and other loads is not infinite. For this reason, an oversized load, or one which operates too many hours per day, will cause problems. These problems range from an interruption of the load to damage to the photovoltaic system or the load.

Loads are described in more detail in Section 2.4.

2.1.3 DC Electricity. Photovoltaic electricity is DC (Direct Current). The current has a polarity, that is, it flows in one direction. This has an impact on wiring methods and equipment.

In photovoltaic systems, grounding methods must be complete and correct. Wire color conventions are critical, not only to protect equipment from reverse polarity, but also to protect service personnel and system users. Section 2.5.7 has more information on polarity and color conventions.

2.1.4 Current-Limited System. When the electrical lines from a utility company's AC power supply are crossed, the resultant short circuit causes an almost infinite current flow. For this reason, fuses and circuit breakers are used to provide over-current protection.

Photovoltaic modules are current-limited. A short-circuited photovoltaic module will produce current only up to a certain level. In fact, a common check of system performance is to deliberately short-circuit the photovoltaic modules and measure the current flow. This does not damage the modules (Figure 2-1).

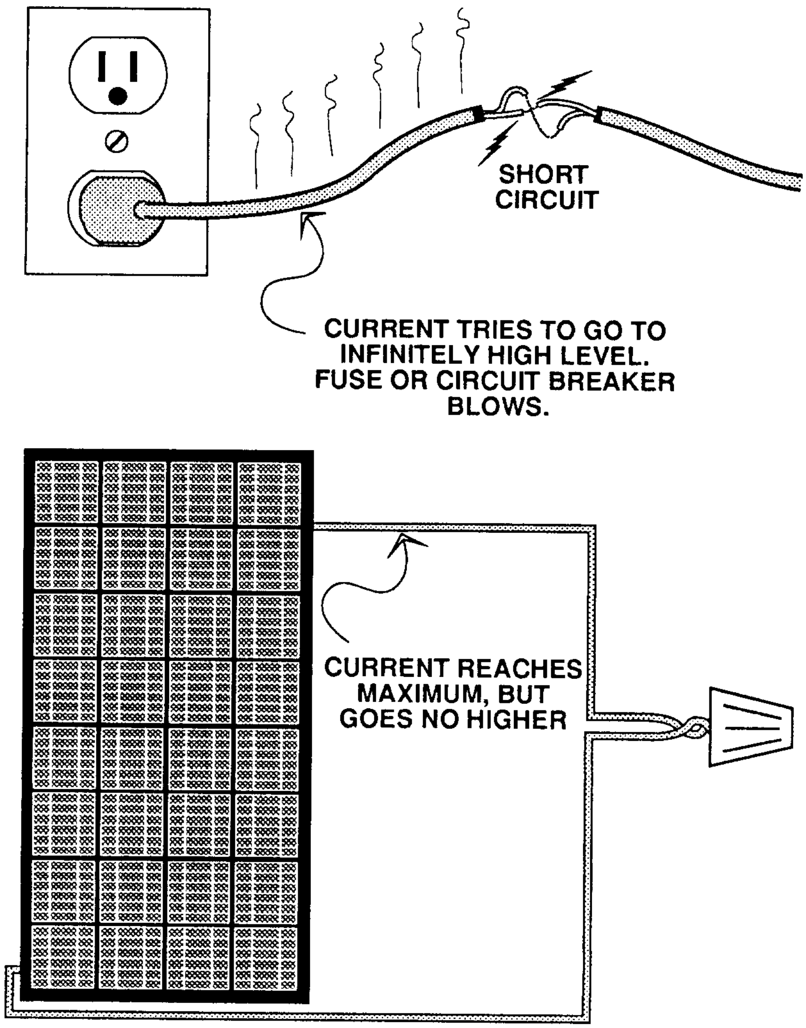


FIGURE 2-1
Short Circuits in AC Circuits (Top) and Photovoltaic Module Circuits (Bottom)

WARNING!

Photovoltaic modules can be short-circuited without damage. However, a short circuit in other system components may cause component damage and dangerous, even lethal, conditions. This is particularly true of storage batteries. Always be sure to open a disconnect switch between the short circuit and the batteries.

Never attempt to short-circuit storage batteries!

2.1.5 Low Voltage Does Not Mean Harmlessness. Whenever working on or around photovoltaic systems remember three very important points:

1) Even at low voltages, photovoltaic systems may be able to deliver substantial current. The amount of available current may be high enough to kill you.

2) Photovoltaic systems can have two power supplies, not just one. Both the batteries and the modules in a system can deliver current.

3) Small "harmless" shocks can still injure you. For example, an arc created when making a wiring connection can ignite the hydrogen gas given off by storage batteries, causing an explosion. Likewise, a small shock can startle you, resulting in a fall from a ladder.

2.1.6 Voltage Drops. Unlike most AC systems, photovoltaic systems can suffer from a substantial voltage drop between the power source and the load. Good design practices minimize this drop.

As an extreme example, the available voltage at the photovoltaic array might be 16 volts. After traveling through hundreds of feet of undersized wire, it could be as low as 11 volts (Figure 2-2).

The system would not be able to recharge a 12 volt storage battery. This is because the available voltage is not higher than the voltage of the battery.

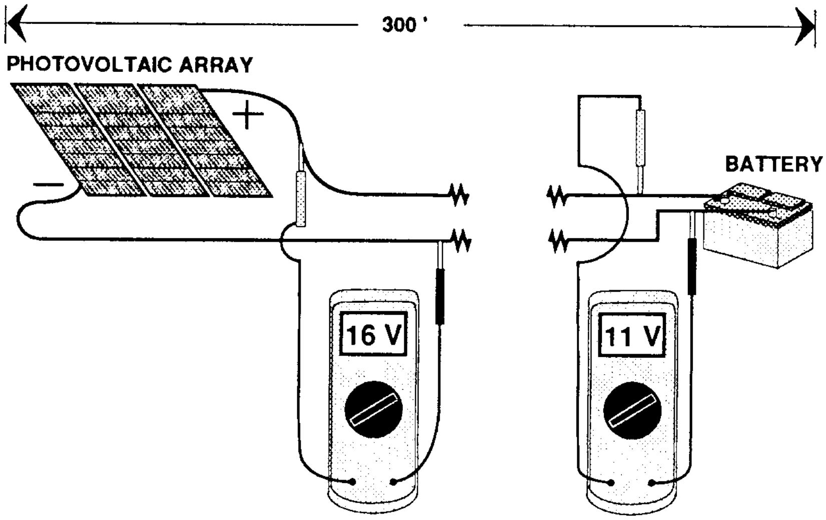


FIGURE 2-2
Voltage Drop in a Photovoltaic System

Wire runs must be kept as short as possible. Wire must be large enough to minimize the voltage drop. Use the charts in Appendix C to determine these sizes. Notice that the wire sizes in photovoltaic systems are much larger than those in AC systems.

2.1.7 Connect/Disconnect Sequences. Unlike AC systems, the sequence of connection and disconnection is critical to many photovoltaic system components.

It should be noted that explosive hydrogen gas may be present near batteries. Making the last connection at the battery may create a spark which could result in an explosion. The best sequence of battery terminal connection might be as follows and as shown in Figure 2.3:

1) positive connection at battery.

2) positive connection at load.

3) negative connection at battery.

4) negative connection at load.

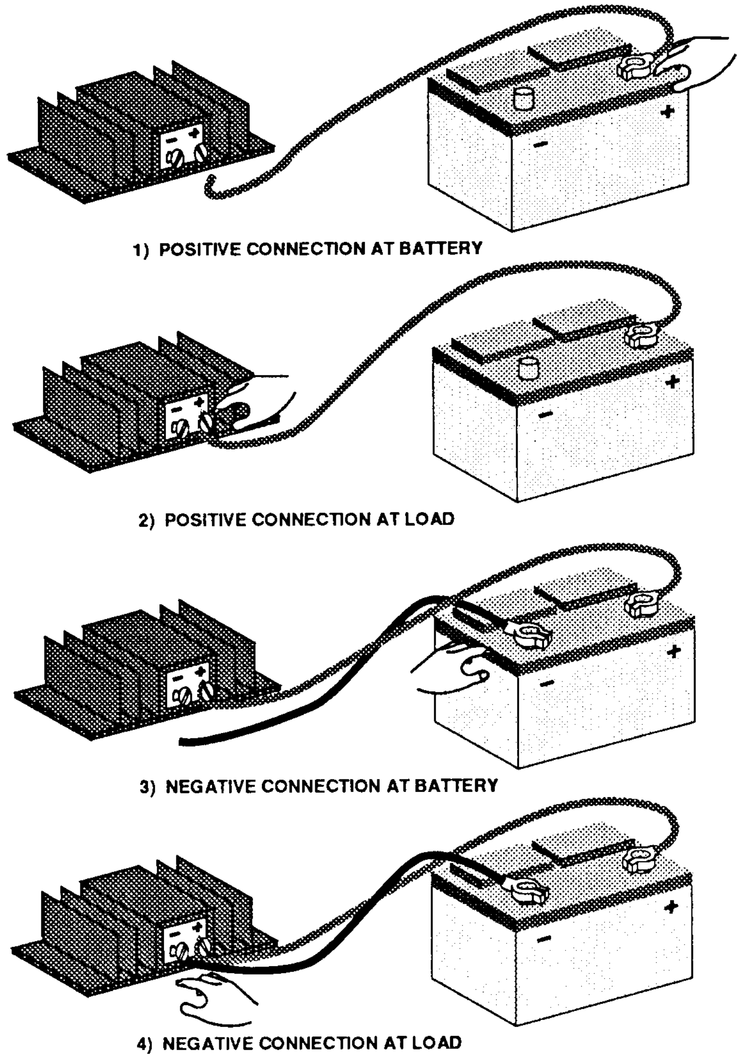


FIGURE 2-3
Battery Terminal
Connection Sequence

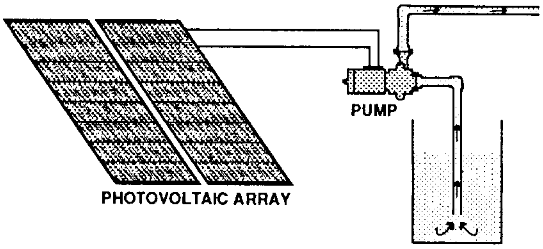
Other components are equally sensitive to connect/disconnect sequences. Charge controllers, in particular, may need to be connected in the correct sequence to prevent damage.

2.2 BASIC SYSTEM CONFIGURATIONS

2.2.1 Direct (Direct Coupled) DC System. The simplest photovoltaic system is made up of an array connected directly to a load. If the array includes more than one module, bypass diodes are used (Figure 2-4).

Applications requiring the most power during the sunniest part of the day are ideal for this type of system. Pumping water for irrigation or to a storage tank, running a fan for ventilation, or operating a pump to collect solar heat are examples of appropriate applications. Lighting and other loads which are rarely used during the daylight hours would probably never be supplied with power by a system of this type.

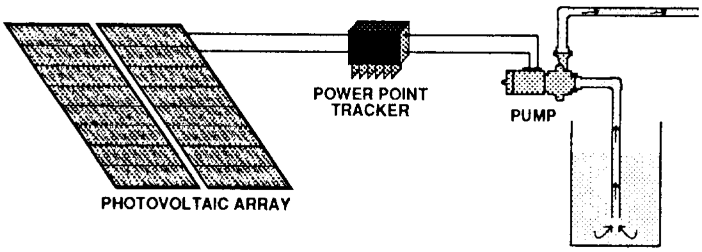
FIGURE 2-4
Direct DC System



The load must run on DC (Direct Current) electricity. This normally means a DC motor is used to run a pump, fan, or other device. As the sunlight gets more intense, the motor runs faster. Thus, the more sunlight, the more water or air that is moved.

2.2.2 Power Point Tracking DC System. The performance of a direct DC system can be increased by adding a power point tracker (Figure 2-5).

FIGURE 2-5
Power Point Tracking
DC System



The power point tracker constantly monitors the system performance and makes electrical adjustments to keep the system operating as close as possible to its maximum output. More information on power point tracking can be found in Section 2.5.5.

2.2.3 Self-Regulated DC System. If battery storage is added to the system, some means must be used to prevent overcharging the batteries. The simplest way to do this is to use self-regulating modules. These modules are designed to deliver a voltage that is too low to overcharge the battery. (Figure 2-6). Careful matching of component sizes and loads is critical.

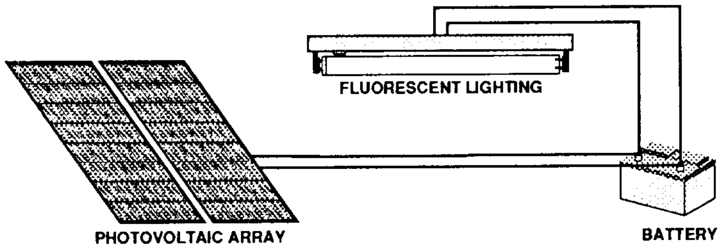


FIGURE 2-6
Self-Regulated DC System

Again, the loads are DC only. If adequate battery storage is provided, and the loads are used consistently, this can be a reliable system. Because electricity is stored, lighting and other devices can be used after dark or during cloudy weather.

2.2.4 Regulated DC System. Most systems do not have self-regulated modules. Furthermore, many systems require some way to prevent damaging the batteries from charge levels which are too high or too low.

A charge controller, sometimes called a charge regulator, is used to keep the batteries from being overcharged. An optional feature of many controllers is a load cutoff. This turns off some or all of the loads whenever the batteries' state of charge gets too low (Figure 2-7).

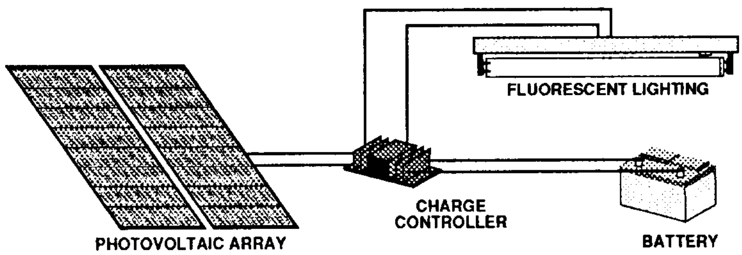


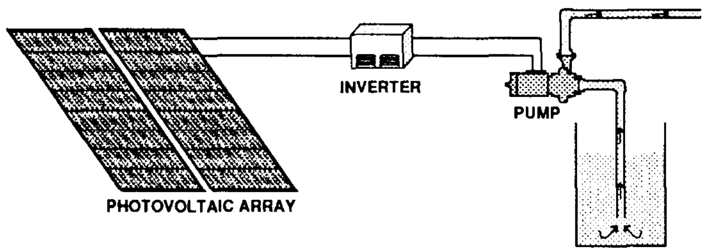
FIGURE 2-7
Regulated DC System

Although the additional component adds to the complexity of the system, draws additional power, and can reduce overall reliability, the charge controller extends the battery life.

This is probably the most common photovoltaic system. More information about charge controllers is in Section 2.5.2.

2.2.5 Direct AC System. In some cases, such as deep well water pumping, AC loads must be provided with power, but only during the day. If the DC output of a photovoltaic array is converted to AC with an inverter, it can supply the AC load directly (Figure 2-8)

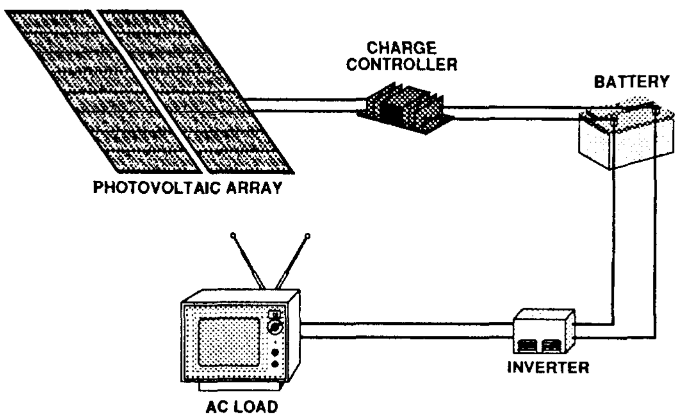
FIGURE 2-8
Direct AC System



This system is appropriate for many of the same situations as the direct DC system. The inverter must be protected from temperature extremes and inclement weather. The cost of an inverter is significant, and it reduces the overall system efficiency. However, if the application requires a device which cannot operate on or be converted to DC, this is the simplest way to do the job.

2.2.6 AC System with Storage. If the AC load must run during periods when the photovoltaic array cannot supply power, battery storage and a charge controller must be included (Figure 2-9).

FIGURE 2-9
AC System with Storage



The combined inefficiencies of the batteries and the inverter reduce overall system performance. Nevertheless, AC applications exist which will require the complexity and expense of this type of photovoltaic system.

2.2.7 Mixed AC/DC System. A good compromise is to supply every possible need with a DC device, and use AC only for those loads for which there is no alternative (Figure 2-10).

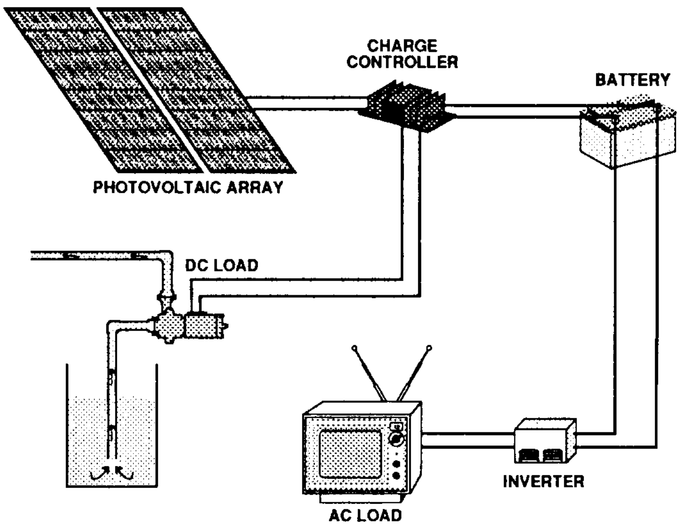


FIGURE 2-10
Mixed AC/DC System

This compromise allows the most effective use of the energy available from the photovoltaic array, while satisfying the load requirements.

2.3 COMPONENT OPERATION

2.3.1 Photovoltaic Cells. At the present time, most commercial photovoltaic cells are manufactured from silicon, the same material from which sand is made. In this case, however, the silicon is extremely pure. Other, more exotic materials such as gallium arsenide are just beginning to make their way into the field.

The four general types of silicon photovoltaic cells are:

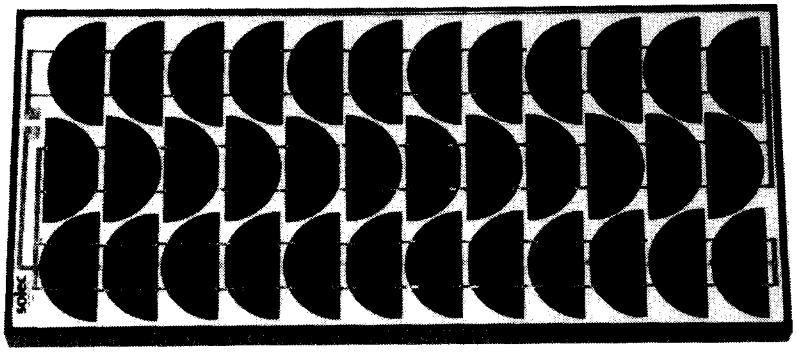
- Single-crystal silicon.
- Polycrystal silicon (also known as multicrystal silicon).
- Ribbon silicon.
- Amorphous silicon (abbreviated as "aSi," also known as thin film silicon).

Single-crystal silicon

Most photovoltaic cells are single-crystal types. To make them, silicon is purified, melted, and crystallized into ingots. The ingots are sliced into thin wafers to make individual cells. The cells have a uniform color, usually blue or black (Figure 2-11).

FIGURE 2-11
Single-Crystal Silicon Cells

Photo Courtesy of Solec International

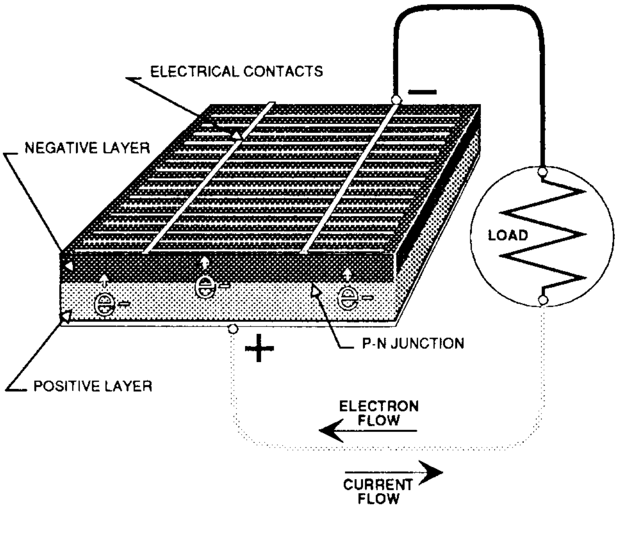


Typically, most of the cell has a slight positive electrical charge. A thin layer at the top has a slight negative charge.

The cell is attached to a base called a "backplane." This is usually a layer of metal used to physically reinforce the cell and to provide an electrical contact at the bottom.

Since the top of the cell must be open to sunlight, a thin grid of metal is applied to the top instead of a continuous layer. The grid must be thin enough to admit adequate amounts of sunlight, but wide enough to carry adequate amounts of electrical energy (Figure 2-12)

FIGURE 2-12
Operation of a Photovoltaic Cell



Light, including sunlight, is sometimes described as particles called "photons." As sunlight strikes a photovoltaic cell, photons move into the cell.

When a photon strikes an electron, it dislodges it, leaving an empty "hole". The loose electron moves toward the top layer of the cell. As photons continue to enter the cell, electrons continue to be dislodged and move upwards (Figure 2-12)

If an electrical path exists outside the cell between the top grid and the backplane of the cell, a flow of electrons begins. Loose electrons move out the top of the cell and into the external electrical circuit. Electrons from further back in the circuit move up to fill the empty electron holes.

Most cells produce a voltage of about one-half volt, regardless of the surface area of the cell. However, the larger the cell, the more current it will produce.

Current and voltage are affected by the resistance of the circuit the cell is in. The amount of available light affects current production. The temperature of the cell affects its voltage. Knowing the electrical performance characteristics of a photovoltaic power supply is important, and is covered in the next section.

Polycrystalline silicon

Polycrystalline cells are manufactured and operate in a similar manner. The difference is that a lower cost silicon is used. This usually results in slightly lower efficiency, but polycrystalline cell manufacturers assert that the cost benefits outweigh the efficiency losses.

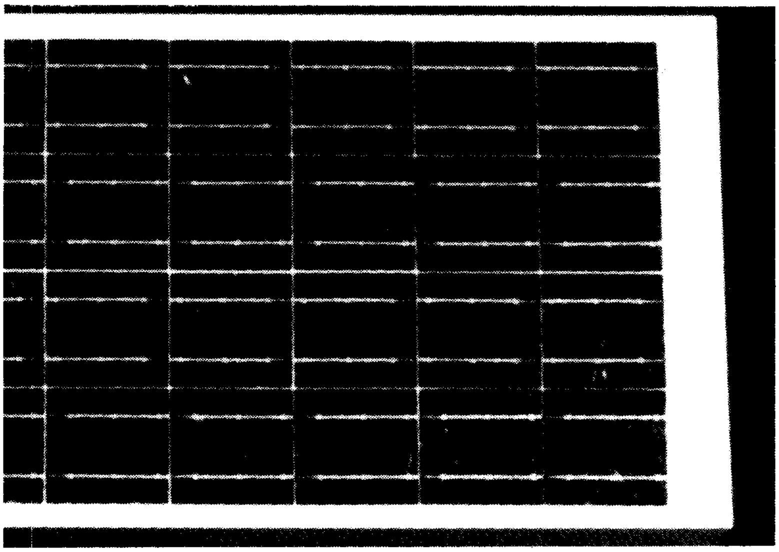


FIGURE 2-13
Polycrystalline Silicon Cells

Photo Courtesy of Kyocera America, Inc.

The surface of polycrystalline cells has a random pattern of crystal borders instead of the solid color of single crystal cells (Figure 2-13).

Ribbon silicon

Ribbon-type photovoltaic cells are made by growing a ribbon from the molten silicon instead of an ingot. These cells operate the same as single and polycrystal cells.

The anti-reflective coating used on most ribbon silicon cells gives them a prismatic rainbow appearance.

Amorphous or thin film silicon

The previous three types of silicon used for photovoltaic cells have a distinct crystal structure. Amorphous silicon has no such structure. Amorphous silicon is sometimes abbreviated "aSi" and is also called thin film silicon.

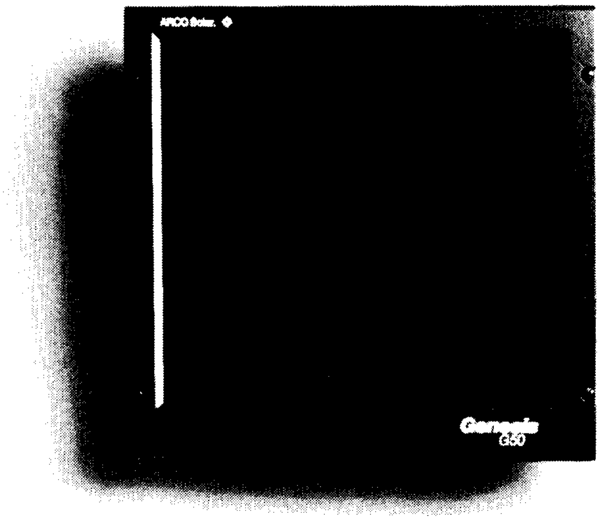
Amorphous silicon units are made by depositing very thin layers of vaporized silicon in a vacuum onto a support of glass, plastic, or metal.

Amorphous silicon cells are produced in a variety of colors (Figure 2-14).

Since they can be made in sizes up to several square yards, they are made up in long rectangular "strip cells." These are connected in series to make up "modules." Modules of all kinds are described in Section 2.3.2.

FIGURE 2-14
An Amorphous Silicon Module

Photo Courtesy of Arco Solar, Inc.



Because the layers of silicon allow some light to pass through, multiple layers can be deposited. The added layers increase the amount of electricity the photovoltaic cell can produce. Each layer can be "tuned" to accept a particular band of light wavelength.

The performance of amorphous silicon cells can drop as much as 15% upon initial exposure to sunlight. This drop takes around six weeks. Manufacturers generally publish post-exposure performance data, so if the module has not been exposed to sunlight, its performance will exceed specifications at first.

The efficiency of amorphous silicon photovoltaic modules is less than half that of the other three technologies. This technology has the potential of being much less expensive to manufacture than crystalline silicon technology. For this reason, research is currently under way to improve amorphous silicon performance and manufacturing processes.

2.3.2 Photovoltaic Modules. For almost all applications, the one-half volt produced by a single cell is inadequate. Therefore, cells are connected together in series to increase the voltage. Several of these series strings of cells may be connected together in parallel to increase the current as well.

These interconnected cells and their electrical connections are then sandwiched between a top layer of glass or clear plastic and a lower level of plastic or plastic and metal. An outer frame is attached to increase mechanical strength, and to provide a way to mount the unit. This package is called a "module" or "panel" (Figure 2-15). Typically, a module is the basic building block of photovoltaic systems. Table 2-1 is a summary of currently available modules.

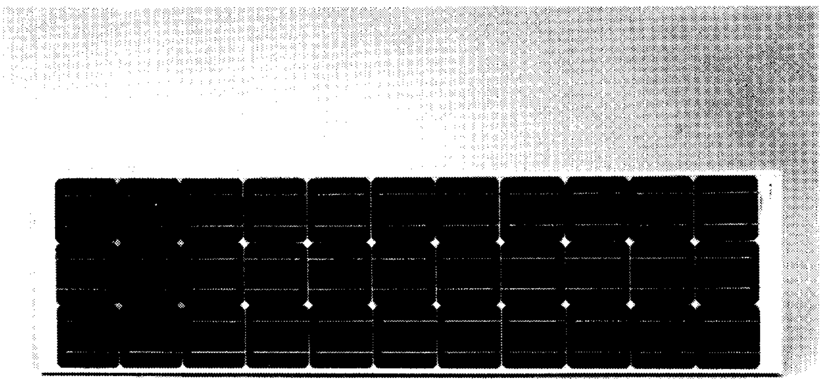


FIGURE 2-15
A Photovoltaic
Module

Photo Courtesy of Arco Solar, Inc.

TABLE 2-1: Summary of Current Photovoltaic Technology

Cell Type	Efficiency Laboratory Record	Efficiency Production Range	Advantages	Disadvantages	Manufacturers	
Single-Crystal Silicon	19.1%	10% to 13%	* Well established and tested technology * Stable * Relatively efficient * Can be made in square cells	* Uses a lot of expensive material * Lots of waste in slicing wafers * Costly to manufacture * Round cells can't be spaced in modules efficiently	Siemens (Germany) Solec International (US) Solarex (US) Tidelands (US) CEL (India) Hoxan (Japan) PB Solar (UK) Pragma (Italy) Ansaldo (Italy) Nippon Electric (Japan) Sharp (Japan)	Helios(Italy) Hitachi (Japan) Mitsubishi (Japan) Kyocera (Japan) Heliodynamica (Brazil) Bharat (India) Siemens (Germany) Isophoton (Spain) Komatsu (Japan)
Poly-crystalline Silicon	18%	10% to 12%	* Well established and tested technology * Stable * Relatively efficient * Less expensive than single crystal silicon * Square cells for more efficient spacing	* Uses a lot of expensive material * Lots of waste in slicing * wafers * Fairly costly to manufacture * Slightly less efficient than single crystal	Solarex (US) Pragma (Italy) Photowatt (France) AEG (Germany) Kyocera (Japan)	
Ribbon Silicon	15%	10% to 12.5%	* Does not require slicing * Less material waste than single crystal and polycrystal * Potential for high speed manufacturing * Relatively efficient	* Has not been scaled up to large volume production * Complex manufacturing process	Mobil Solar (US) Westinghouse (US)	
Amorphous (US) or Thin Film Silicon	11.5% Fuji (Japan)	to 8%	4% * Potential for highly automated and very rapid production * Potential for very low cost * Less affected by shading when built with diodes	* Very low material use power output * Low efficiency	* Pronounced degradation in Chronar (US) Solarex (US) Sovonics (US) Sanyo (Japan)	Arco Solar ECD/Sharp (Japan) Kaneka (Japan) Taiyo Yuden (Japan)

* *This chart originally appeared in Alternative Sources of Energy Magazine, Issue #81, May 1986. For subscription information write to them at 107 S. Central Ave., Milaca, MN 56353.*

Groups of modules can be interconnected in series and/or parallel to form an "array." By adding "balance of system" (BOS) components such as storage batteries, charge controllers, and power conditioning devices, we have a complete photovoltaic system.

2.3.3 Describing Photovoltaic Module Performance. To insure compatibility with storage batteries or loads, it is necessary to know the electrical characteristics of photovoltaic modules.

As a reminder, "I" is the abbreviation for current, expressed in amps. "V" is used for voltage in volts, and "R" is used for resistance in ohms.

A photovoltaic module will produce its maximum current when there is essentially no resistance in the circuit. This would be a short circuit between its positive and negative terminals.

This maximum current is called the short circuit current, abbreviated $I_{(sc)}$. When the module is shorted, the voltage in the circuit is zero.

Conversely, the maximum voltage is produced when there is a break in the circuit. This is called the open circuit voltage, abbreviated $V_{(oc)}$. Under this condition the resistance is infinitely high and there is no current, since the circuit is incomplete.

These two extremes in load resistance, and the whole range of conditions in between them, are depicted on a graph called a I-V (current-voltage) curve. Current, expressed in amps, is on the vertical Y-axis. Voltage, in volts, is on the horizontal X-axis (Figure 2-16).

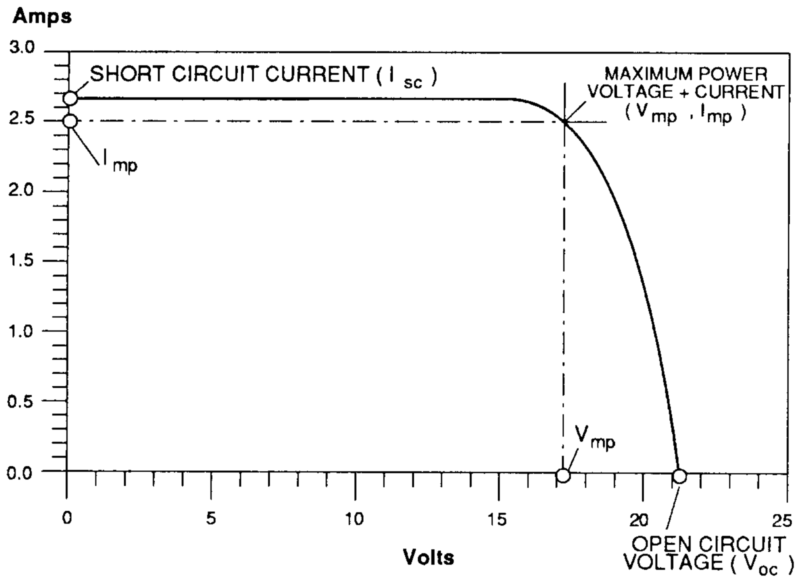


FIGURE 2-16
A Typical Current-Voltage Curve

As you can see in Figure 2-16, the short circuit current occurs on a point on the curve where the voltage is zero. The open circuit voltage occurs where the current is zero.

The power available from a photovoltaic module at any point along the curve is expressed in watts. Watts are calculated by multiplying the voltage times the current (watts = volts x amps, or W = VA).

At the short circuit current point, the power output is zero, since the voltage is zero.

At the open circuit voltage point, the power output is also zero, but this time it is because the current is zero.

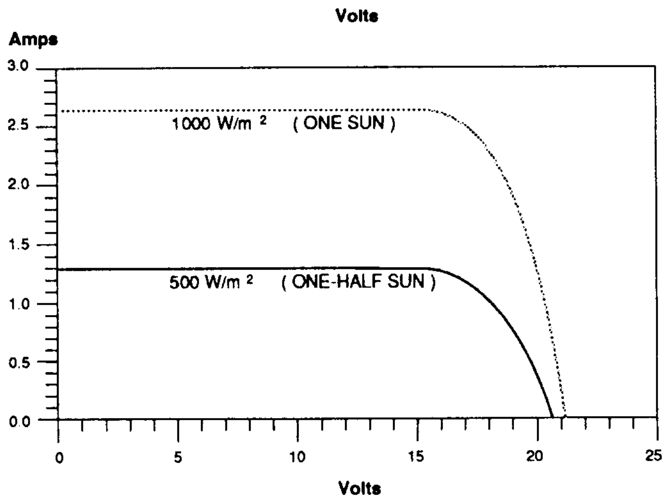
There is a point on the "knee" of the curve where the maximum power output is located. This point on our example curve is where the voltage is 17 volts, and the current is 2.5 amps. Therefore the maximum power in watts is 17 volts times 2.5 amps, equaling 42.5 watts.

The power, expressed in watts, at the maximum power point is described as peak, maximum, or ideal, among other terms. Maximum power is generally abbreviated as "$I_{(mp)}$." Various manufacturers call it maximum output power, output, peak power, rated power, or other terms.

The current-voltage (I-V) curve is based on the module being under standard conditions of sunlight and module temperature. It assumes there is no shading on the module.

Standard sunlight conditions on a clear day are assumed to be 1000 watts of solar energy per square meter (1000 W/m^2 or 1kW/m^2). This is sometimes called "one sun," or a "peak sun." Less than one sun will reduce the current output of the module by a proportional amount. For example, if only one-half sun (500 W/m^2) is available, the amount of output current is <u>roughly</u> cut in half (Figure 2-17).

FIGURE 2-17
A Typical
Current-Voltage Curve
at One Sun and
One-Half Sun



For maximum output, the face of the photovoltaic modules should be pointed as straight toward the sun as possible. Section 2.3.5 contains information on determining the correct direction and module tilt angle for various locations and applications.

Because photovoltaic cells are electrical semiconductors, partial shading of the module will cause the shaded cells to heat up. They are now acting as inefficient conductors instead of electrical generators. Partial shading may ruin shaded cells.

Partial module shading has a serious effect on module power output. For a typical module, completely shading only one cell can reduce the module output by as much as 80% (Figure 2-18). One or more damaged cells in a module can have the same effect as shading.

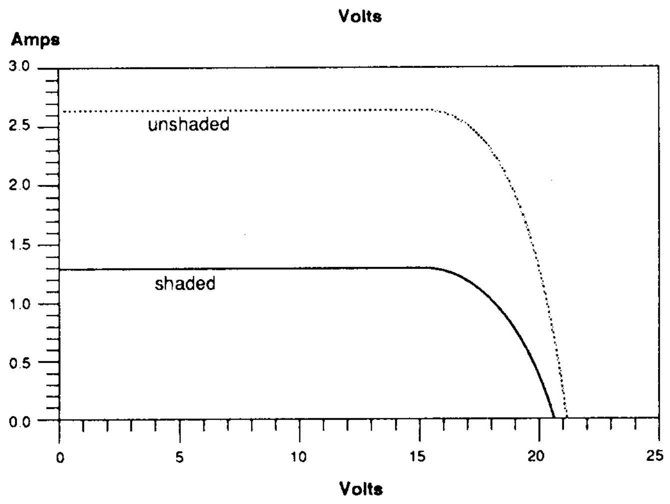


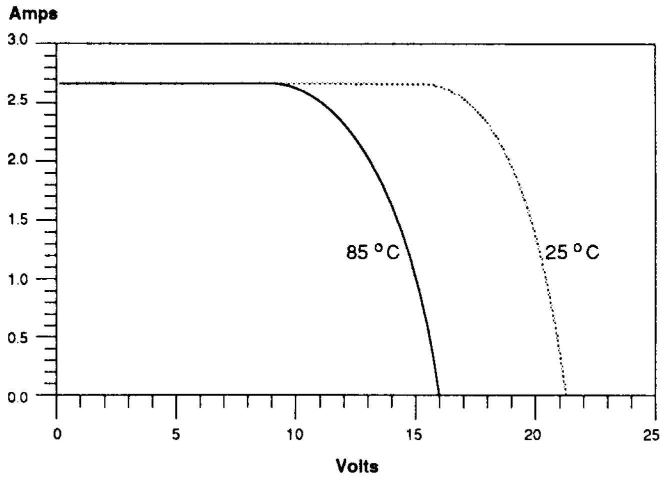
FIGURE 2-18
A Typical Current-Voltage Curve for an Unshaded Module and for a Module with One Shaded Cell

This is why modules should be completely unshaded during operation. A shadow across a module can almost stop electricity production. Thin film modules are not as affected by this problem, but they should still be unshaded.

Module temperature affects the output voltage inversely. Higher module temperatures will reduce the voltage by 0.04 to 0.1 volts for every one Celsius degree rise in temperature (0.04V/°C to 0.1V/°C). In Fahrenheit degrees, the voltage loss is from 0.022 to 0.056 volts per degree of temperature rise (Figure 2-19).

This is why modules should not be installed flush against a surface. Air should be allowed to circulate behind the back of each module so its temperature does not rise and reducing its output. An air space of 4 - 6 inches is usually required to provide proper ventilation.

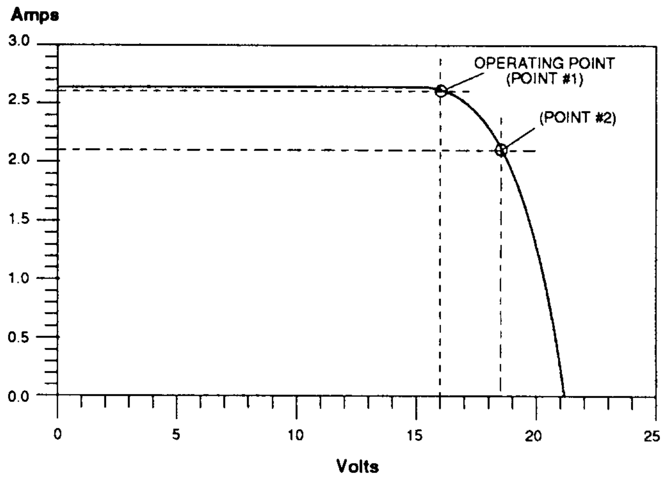
FIGURE 2-19
A Typical
Current-Voltage Curve
for a Module at
25°C (77°F) and
85°C (185°F)



The last significant factor which determines the power output of a module is the resistance of the system to which it is connected. If the module is charging a battery, it must supply a higher voltage than that of the battery.

If the battery is deeply discharged, the battery voltage is fairly low. The photovoltaic module can charge the battery with a low voltage, shown as point #1 in Figure 2-20. As the battery reaches a full charge, the module is forced to deliver a higher voltage, shown as point #2. The battery voltage drives module voltage.

FIGURE 2-20:
Operating Voltages
During a Battery
Charging Cycle



Eventually, the required voltage is higher than the voltage at the module's maximum power point. At this operating point, the current production is lower than the current at the maximum power point. The module's power output is also lower.

To a lesser degree, when the operating voltage is lower than that of the maximum power point (point #1), the output power is lower than the maximum. Since the ability of the module to produce electricity is not being completely used whenever it is operating at a point fairly far from the maximum power point, photovoltaic modules should be carefully matched to the system load and storage.

Using a module with a maximum voltage which is too high should be avoided nearly as much as using one with a maximum voltage which is too low.

The output voltage of a module depends on the number of cells connected in series. Typical modules use either 30, 32, 33, 36, or 44 cells wired in series.

The modules with 30-32 cells are considered self regulating modules. 36 cell modules are the most common in the photovoltaic industry. Their slightly higher voltage rating, 16.7 volts, allows the modules to overcome the reduction in output voltage when the modules are operating at high temperatures.

Modules with 33 - 36 cells also have enough surplus voltage to effectively charge high antimony content deep cycle batteries. However, since these modules can overcharge batteries, they usually require a charge controller.

Finally, 44 cell modules are available with a rated output voltage of 20.3 volts. These modules are typically used only when a substantially higher voltage is required.

As an example, if the module is sometimes forced to operate at high temperatures, it can still supply enough voltage to charge 12 volt batteries.

Another application for 44 cell modules is a system with an extremely long wire run between the modules and the batteries or load. If the wire is not large enough, it will cause a significant voltage drop. Higher module voltage can overcome this problem.

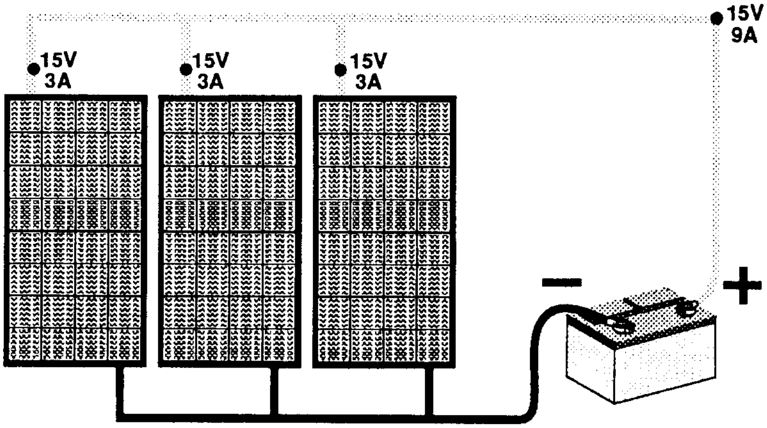
It should be noted that this approach is similar to putting a larger engine in a car with locked brakes to make it move faster. It is almost always more cost-effective to use an adequate wire size, rather than to overcome voltage drop problems with more costly 44 cell modules.

Section 2.5.5 discusses maximum power point trackers. These devices are used to bring the module to a point as close as possible to the maximum power point. They are used mostly in direct DC systems, particularly with DC motors for pumping.

2.3.4 Photovoltaic Arrays. In many applications the power available from one module is inadequate for the load. Individual modules can be connected in series, parallel, or both to increase either output voltage or current. This also increases the output power.

When modules are connected in parallel, the current increases. For example, three modules which produce 15 volts and 3 amps each, connected in parallel, will produce 15 volts and 9 amps (Figure 2-21).

FIGURE 2-21
Three Modules
Connected in Parallel



If the system includes a battery storage system, a reverse flow of current from the batteries through the photovoltaic array can occur at night. This flow will drain power from the batteries.

A diode is used to stop this reverse current flow. Diodes are electrical devices which only allow current to flow in one direction (Figure 2-22). A blocking diode is shown in the array in Figure 2-23.

Diodes with the least amount of voltage drop are called schottky diodes, typically dropping .3 volts instead of .7 volts as in silicon diodes.

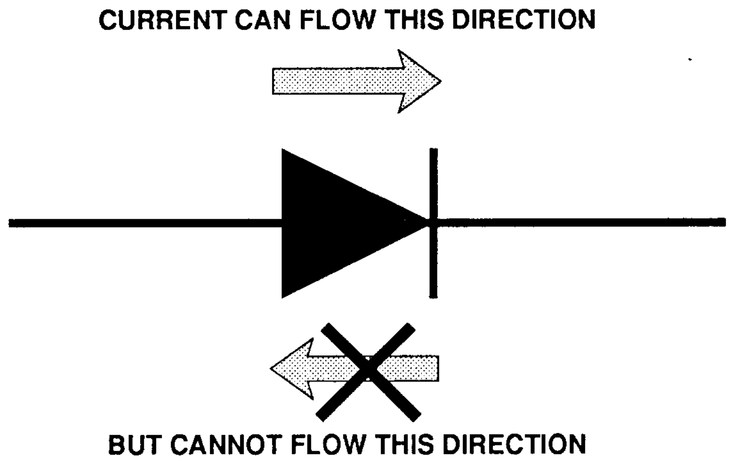


FIGURE 2-22
Basic Operation of a Diode

Because diodes create a voltage drop, some systems use a controller which opens the circuit instead of using a blocking diode.

If the same three modules are connected in series, the output voltage will be 45 volts, and the current will be 3 amps.

If one module in a series string fails, it provides so much resistance that other modules in the string may not be able to operate either. A bypass path around the disabled module will eliminate this problem (Figure 2-23). The bypass diode allows the current from the other modules to flow through in the "right" direction.

Many modules are supplied with a bypass diode right at their electrical terminals. Larger modules may consist of three groups of cells, each with its own bypass diode.

Built in bypass diodes are usually adequate unless the series string produces 48 volts or higher, or serious shading occurs regularly.

Combinations of series and parallel connections are also used in arrays (Figure 2-24). If parallel groups of modules are connected in a series string, large bypass diodes are usually required.

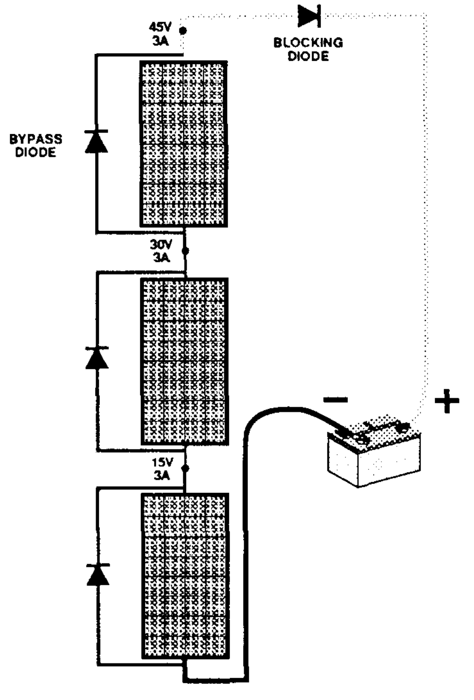


FIGURE 2-23
Three Modules
Connected in Series
with a Blocking Diode
and Bypass Diodes

Isolation diodes are used to prevent the power from the rest of an array from flowing through a damaged series string of modules. They operate like a blocking diode. They are normally required when the array produces 48 volts or more. If isolation diodes are used on every series string, a blocking diode is normally not required.

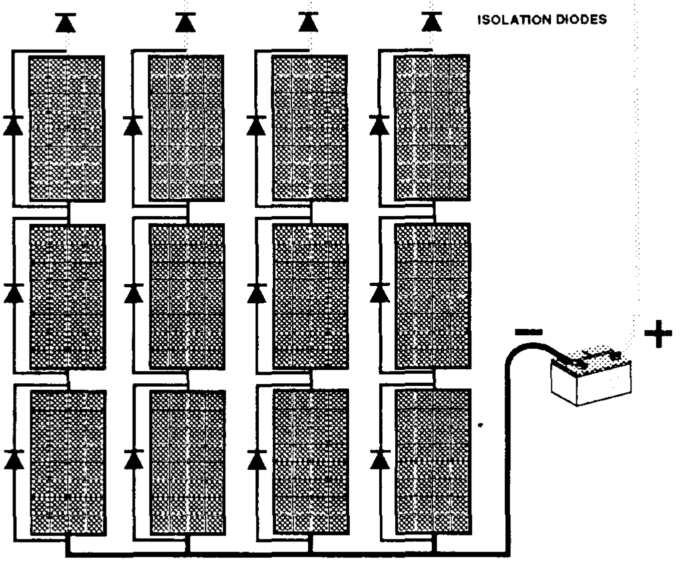


FIGURE 2-24
Twelve Modules in a
Parallel-Series Array
with Bypass Diodes
and Isolation Diodes

Flat-plate stationary arrays

Stationary arrays are the most common. Some allow adjustments in their tilt angle from the horizontal. These changes can be made any number of times throughout the year, although they are normally changed only twice a year. The modules in the array do not move throughout the day (Figure 2-25).

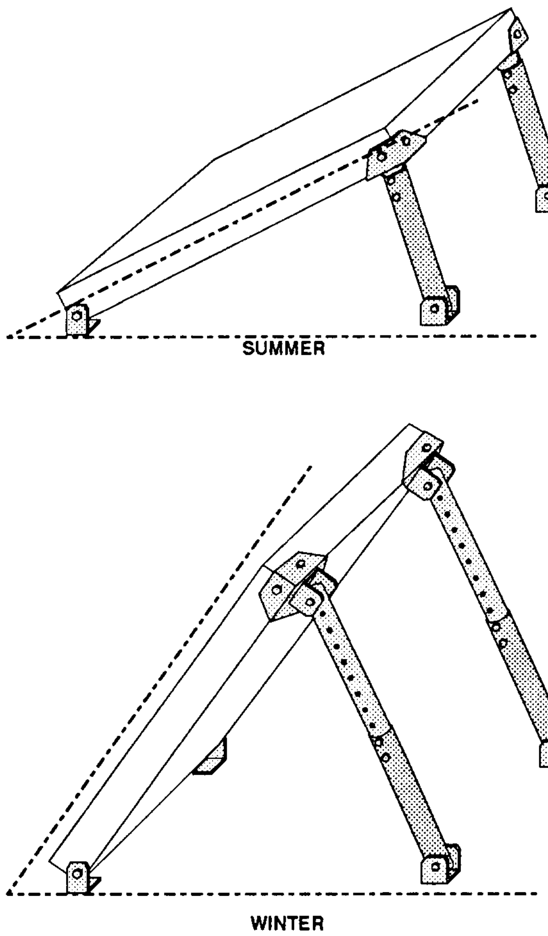


FIGURE 2-25
Adjustable Array Tilted for Summer and Winter Solar Angles

Although a stationary array does not capture as much energy as a tracking array that follows the sun across the sky, and more modules may be required, there are no moving parts to fail. This reliability is why a stationary array is often used for remote or dangerous locations. Section 2.3.5 contains information on determining the correct tilt angle and orientation for different photovoltaic applications.

Portable arrays

A portable array may be as small as a one square foot module easily carried by one person to recharge batteries for communications or flashlights. They can be mounted on vehicles to maintain the engine battery during long periods of inactivity. Larger ones can be installed on trailers or truck beds to provide a portable power supply for field operations (Figures 2-26 and 2-27).

FIGURE 2-26
Personal Photovoltaic Array

Photo Courtesy of Arco Solar, Inc.

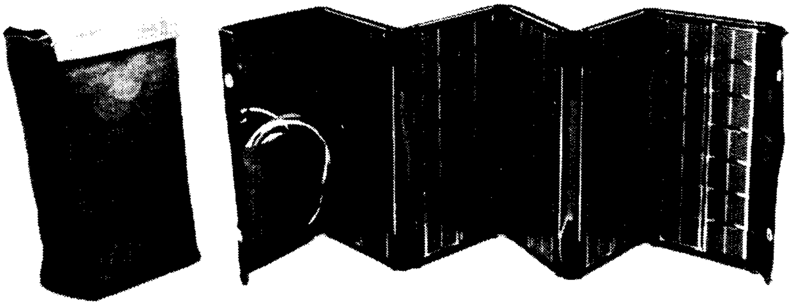
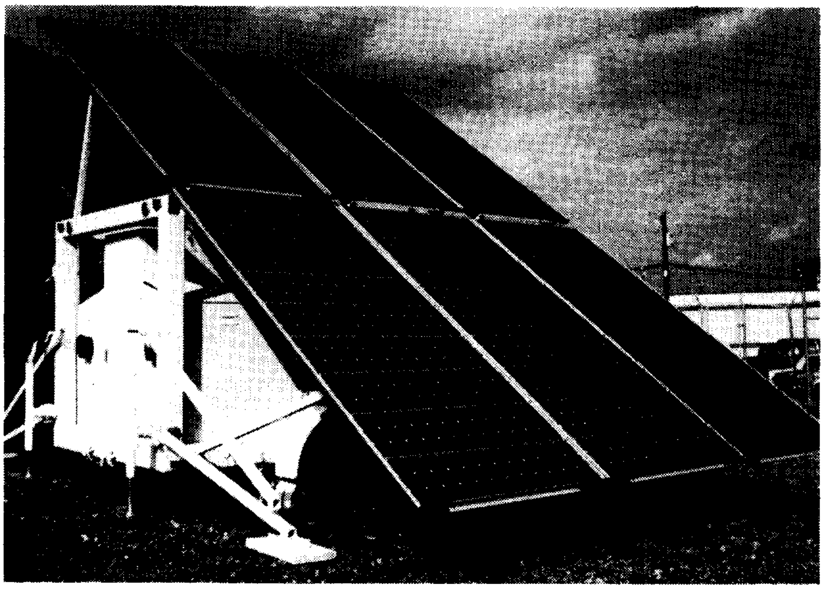


FIGURE 2-27
Portable Power Supply

Photo Courtesy of Integrated Power Corp.



Tracking arrays

Arrays that track, or follow the sun across the sky, can follow the sun in one axis or in two (Figure 2-28). Tracking arrays perform best in areas with very clear climates. This is because following the sun yields significantly greater amounts of energy when the sun's energy is predominantly direct. Direct radiation comes straight from the sun, rather than the entire sky.

Normally, one axis trackers follow the sun from the east to the west throughout the day. The angle between the modules and the ground does not change. The modules face in the "compass" direction of the sun, but may not point exactly up at the sun at all times.

Two axis trackers change both their east-west direction and the angle from the ground during the day. The modules face straight at the sun all through the day. Two axis trackers are considerably more complicated than one axis types.

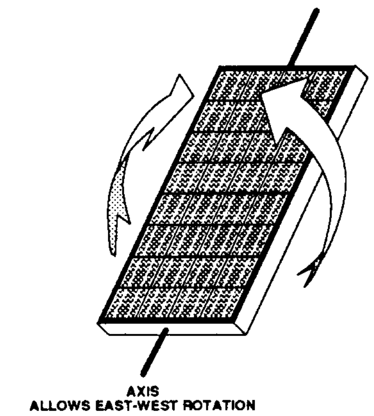
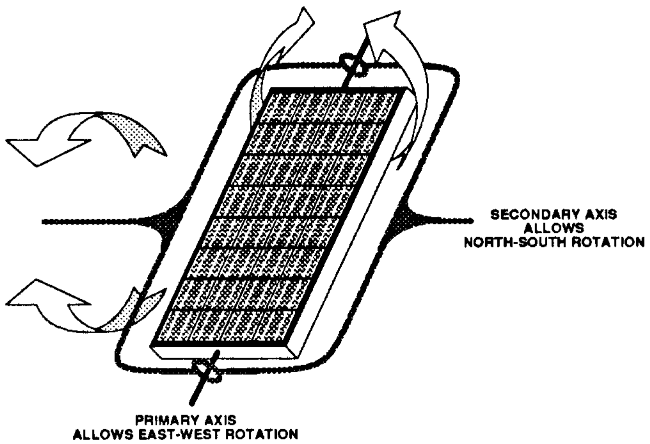


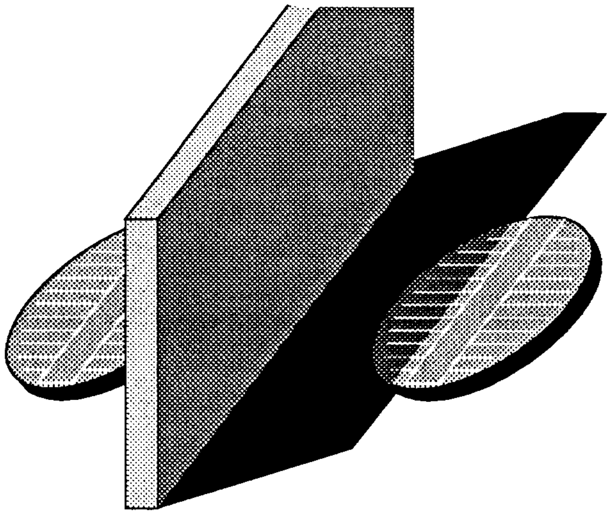
FIGURE 2-28
One Axis and Two
Axis Tracking Arrays



Three basic tracking methods are used. The first uses simple motor, gear, and chain systems to move the array. The system is designed to mechanically point the modules in the direction the sun should be. No sensors or devices actually confirm that the modules are facing the right way.

The second method uses photovoltaic cells as sensors to orient the larger modules in the array. This can be done by placing a cell on each side of a small divider, and mounting the package so it is facing the same way as the modules (Figure 2-29).

FIGURE 2-29
Photovoltaic Cells
Used as Solar
Orientation Sensor



An electronic device constantly compares the small current flow from both cells. If one is shaded, the device triggers a motor to move the array until both cells are exposed to equal amounts of sunlight.

At night or during cloudy weather, the output of both sensor cells is equally low, so no adjustments are made. When the sun comes back up in the morning, the array will move back to the east to follow the sun again.

Although both methods of tracking with motors are quite accurate, there is a "parasitic" power consumption. The motors take up some of the energy the photovoltaic system produces.

A method which has no parasitic consumption uses two small photovoltaic modules to power a reversible gear motor directly. If both modules are in equal sunlight, as shown in Figure 2-30, current flows through the modules and none flows through the motor.

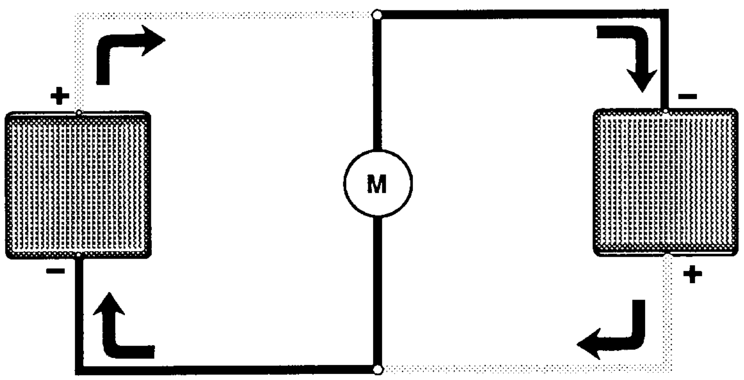


FIGURE 2-30
Current Flow with
Both Modules in
Equal Sunlight

If the right module is shaded, it acts as a resistor (Figure 2-31). Now the current will flow through the motor, turning it in one direction.

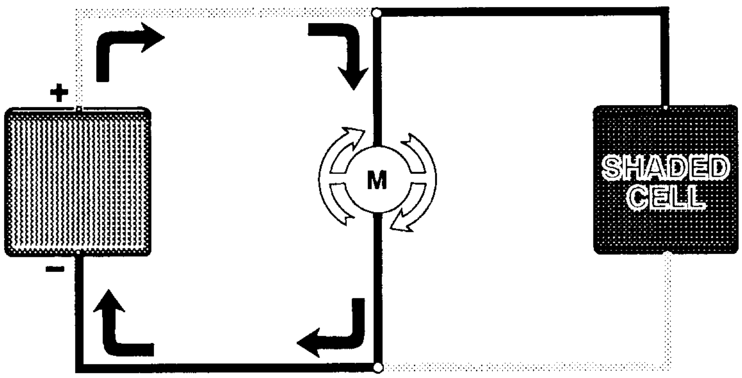


FIGURE 2-31
Current Flow with
One Module Shaded

If the other module, shown in Figure 2-32 on the left, is shaded, the current from the right module flows in the opposite direction. The motor will turn in the opposite direction as well.

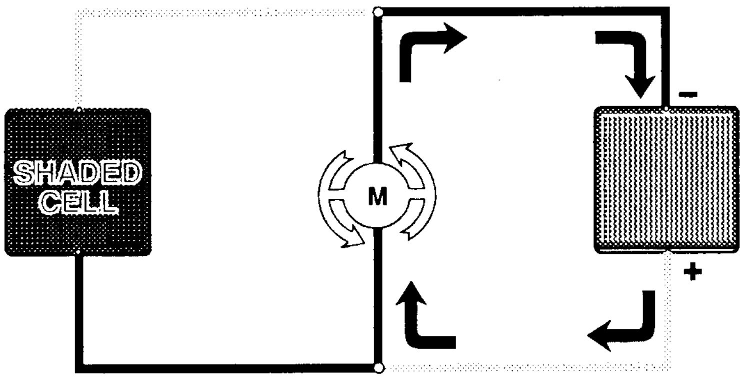


FIGURE 2-32
Current Flow with the
Other Module Shaded

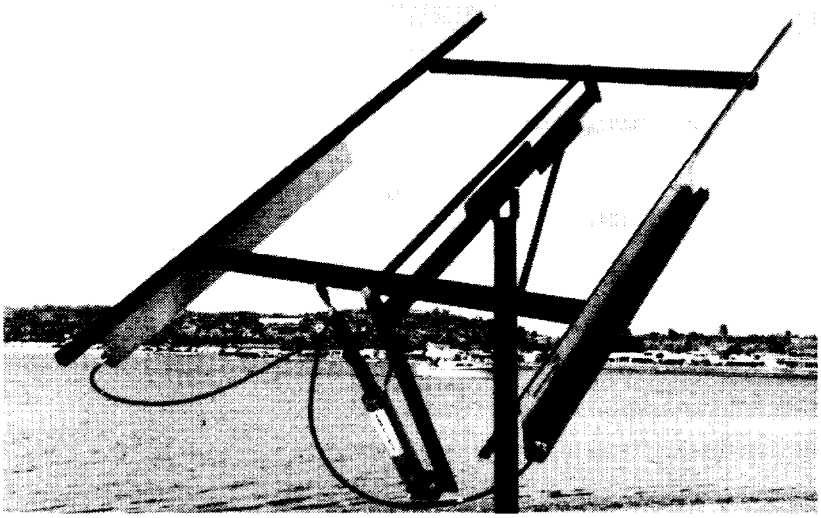
The motor must be able to turn in both directions.

A third tracking method uses the expansion and contraction of fluids to move the array. Generally, a container is filled with a fluid that vaporizes and expands considerably whenever it is in the sun. It condenses and contracts similarly when in the shade. These "passive" tracking methods have proven to be reliable and durable, even in high wind situations.

One system, the "SUN SEEKER" ™ from Robbins Engineering, uses the pressure of the expansion and contraction to operate a hydraulic cylinder. Flexible piping from two containers filled with freon goes to opposite sides of a piston in the cylinder (Figure 2-33).

FIGURE 2-33
SUN SEEKER ™
System without Modules

Photo Courtesy of
Robbins Engineering, Inc.



If the array is facing the sun, the pressure in both containers stays the same, and the piston will not move in the cylinder. However, when the sun moves, the shading on the containers changes, placing them under different pressures.

The pressure difference, brought to the cylinder by the piping, will move the piston. The shaft from the piston will move the array. When the array is pointed back at the sun, the pressure stops increasing in the cylinder, and the piston and rod stop moving.

Another way to move the array with an expansive fluid is to use the change in fluid weight when it vaporizes. The Solar Track Rack ™ by Zomeworks uses this method (Figures 2-34 and 2-35).

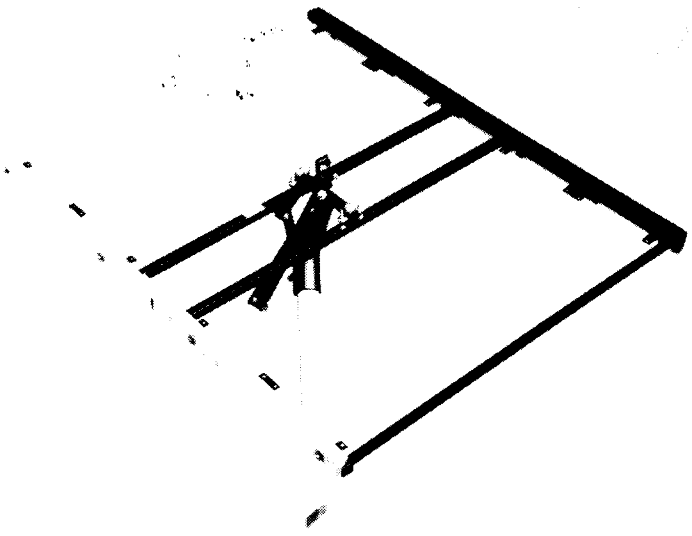


FIGURE 2-34
Solar Track Rack ™
without Modules

Photo Courtesy of Zomeworks Corp.

The fluid-filled containers are integrated into the sides of the array mounting structure. They are connected together flexible piping, which is protected in the mounting structure. As long as the array is facing directly at the sun, the shades cover each container equally.

When the array is no longer facing directly at the sun, one container is exposed to more heat from the sun. This causes the fluid in that container to boil out of that container into the other one. Now the shaded container has more fluid in it and is heavier. The array will drop down like a "teeter-totter" in the direction of the shaded container until the shading equalizes on the two containers again.

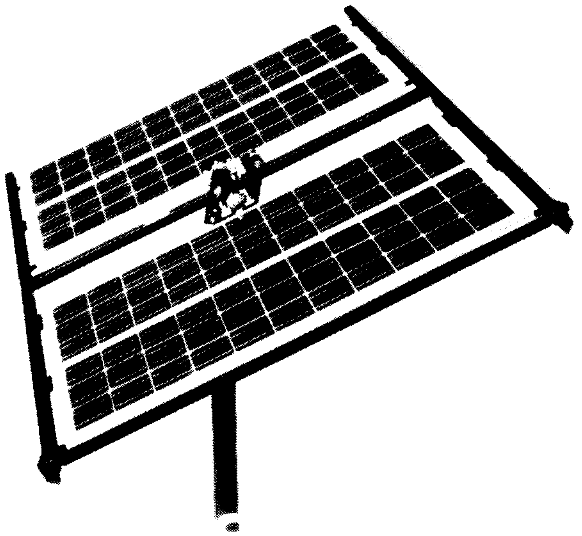


FIGURE 2-35
Solar Track Rack ™
with Modules
Mounted

Photo Courtesy of Zomeworks Corp.

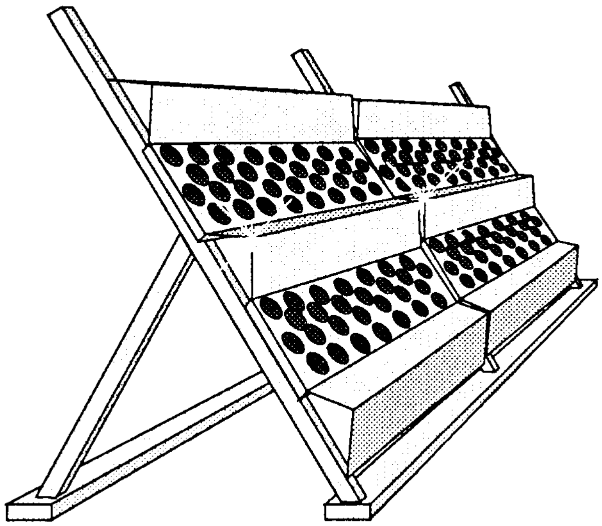
Since this method is more sensitive, wind can move the array. A shock absorber is included in the system to absorb such rapidly applied forces.

Reflectors

Reflectors are sometimes used to increase the amount of solar energy striking the modules (Figure 2-36). Since reflectors cost less than photovoltaic modules, this method may be used for some applications. There are several problems with reflectors, however.

Not all photovoltaic modules are designed for the higher temperatures reflectors cause. The performance and physical structure of many modules will suffer if reflectors are used with them. Remember that higher module temperatures mean lower output voltages.

FIGURE 2-36
Reflectors on a Fixed Photovoltaic Array



Another problem is that reflectors work mostly with sunlight coming directly from the sun. Since a great deal of the sun's energy in cloudy climates comes to the earth's surface from all parts of the sky, reflectors are most effective in clear climates.

In all but the clearest of climates, the amount of direct solar energy is rarely high enough to justify the use of reflectors all year.

By increasing the overall surface area of the array, reflectors also increase the array's wind loading characteristics.

Finally, some type of tracking system may be required. This increases the system cost, may add a parasitic power loss, and can reduce the system reliability. Poorly designed or improperly installed reflectors have been known to shade modules.

Concentrators

Concentrators use lenses or parabolic reflectors to focus light from a larger area onto a photovoltaic cell of smaller area. The cells are spread out more than a typical module, and must be a high temperature type. They may have a heat removal system to keep module temperatures down and output voltages up. These systems have the same disadvantages of reflectors, and are higher in cost. As a consequence, large systems feeding a utility grid are usually the only ones using reflectors or concentrators.

Bracket mounting

Small arrays of one or two modules can use simple brackets to secure the modules individually to a secure surface (Figure 2-25). The surface may be a roof, wall, post, pole, or vehicle. Brackets can include some method to adjust the tilt angle of the module.

The brackets are usually aluminum. If steel is used, it should be painted or treated to prevent corrosion. Galvanized steel is normally avoided, because the continuous grounding used on arrays aggravates the galvanic corrosion that occurs between galvanized steel and almost all other metals.

Fastener hardware should be stainless steel or cadmium plated to prevent corrosion. Identical metals should be used for components and fasteners whenever possible.

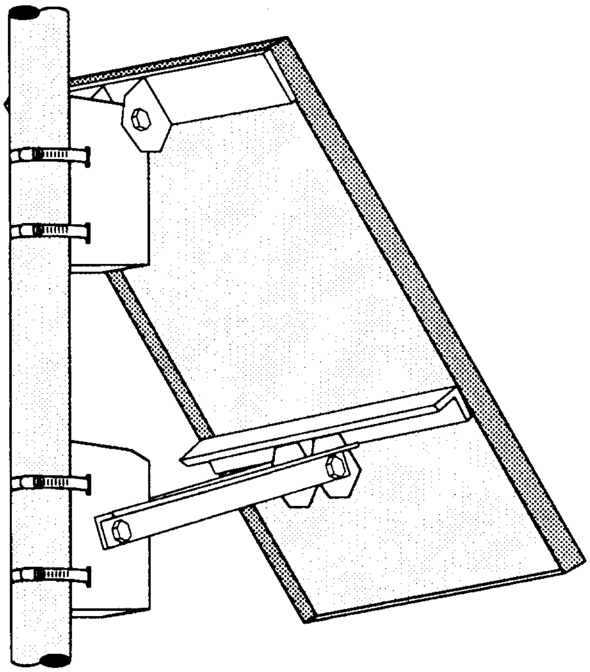
Pole mounting

Typically, up to four modules can be connected together and mounted on a pole (Figure 2-37). Typically, 2 1/2 " nominal steel pipe (O.D. of 3") is used.

Black iron or steel pipe can be used, if painted. Galvanized pipe, rarely available in this size, can be used if compatible fasteners are used. Larger arrays can be pole mounted, if hardware sizes are appropriately increased.

The same types of materials used for bracket mounting should be used for pole mounting.

FIGURE 2-37
Pole Mount of
Photovoltaic Array



Ground mounting

For arrays of eight or more modules, ground mounting is usually the most appropriate technique. The greatest concern is often the uplifting force of wind on the array. This is why most ground mounted arrays are on some kind of sturdy base, usually concrete.

Concrete bases are either piers, a slab with thicker edges, or footings at the front and rear of the array (Figure 2-38). All three usually include a steel reinforcement bar.

In some remote sites it may be more desirable to use concrete block instead of poured concrete. The best way to do this is to use two-web bond-beam block, reinforce it with steel, and fill the space between the webs with concrete or mortar.

Pressure-treated wood of adequate size is sometimes used for ground mounting. This can work well in fairly dry climates, but only if the beams are securely anchored to the ground, and regular inspection and maintenance is provided.

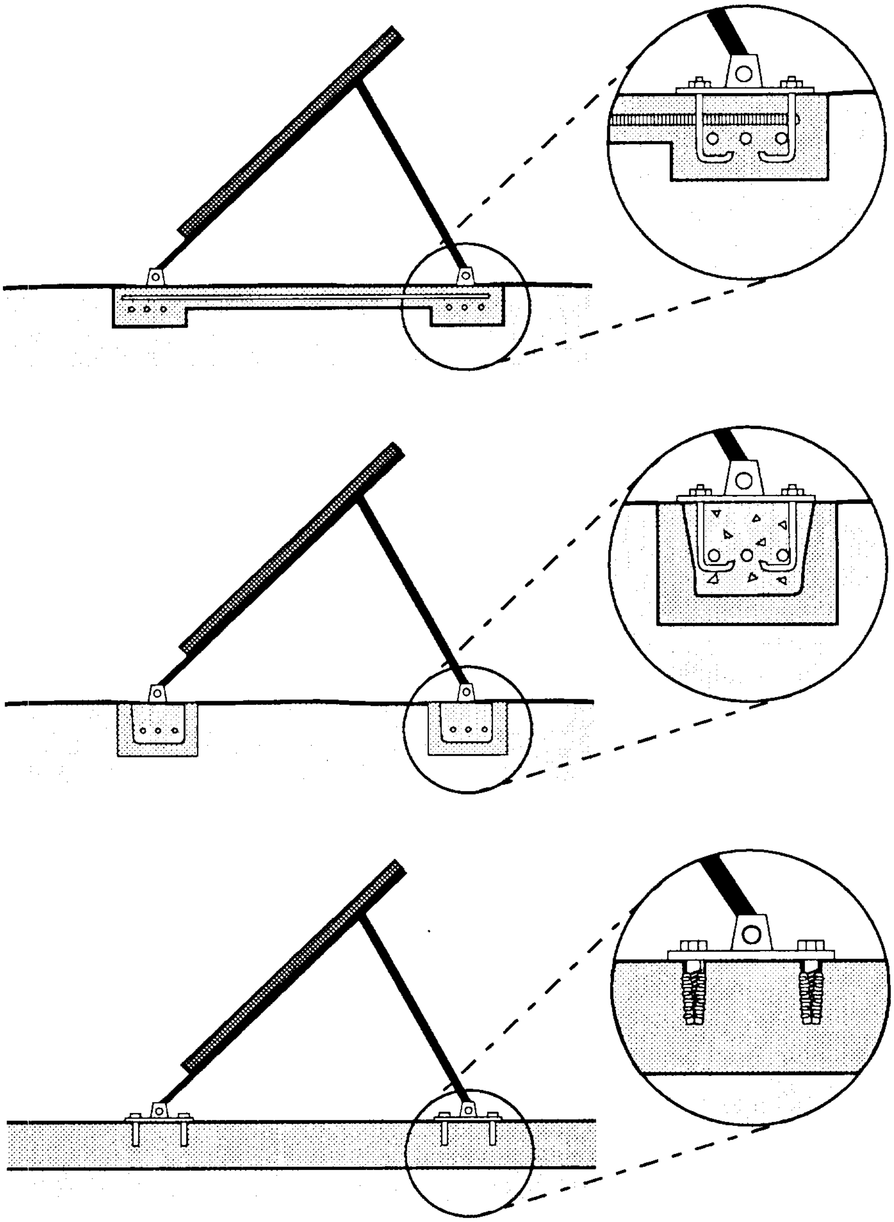


FIGURE 2-38
Concrete Bases

The array's mounting hardware can be bolted to an existing slab. With extensive shimming, some mountaintop arrays are bolted to exposed rock. In either case, adequately sized expansion-type anchor bolts are used. The heads of the bolts should be covered with some type of weatherproof sealant. Silicone sealant is the best choice.

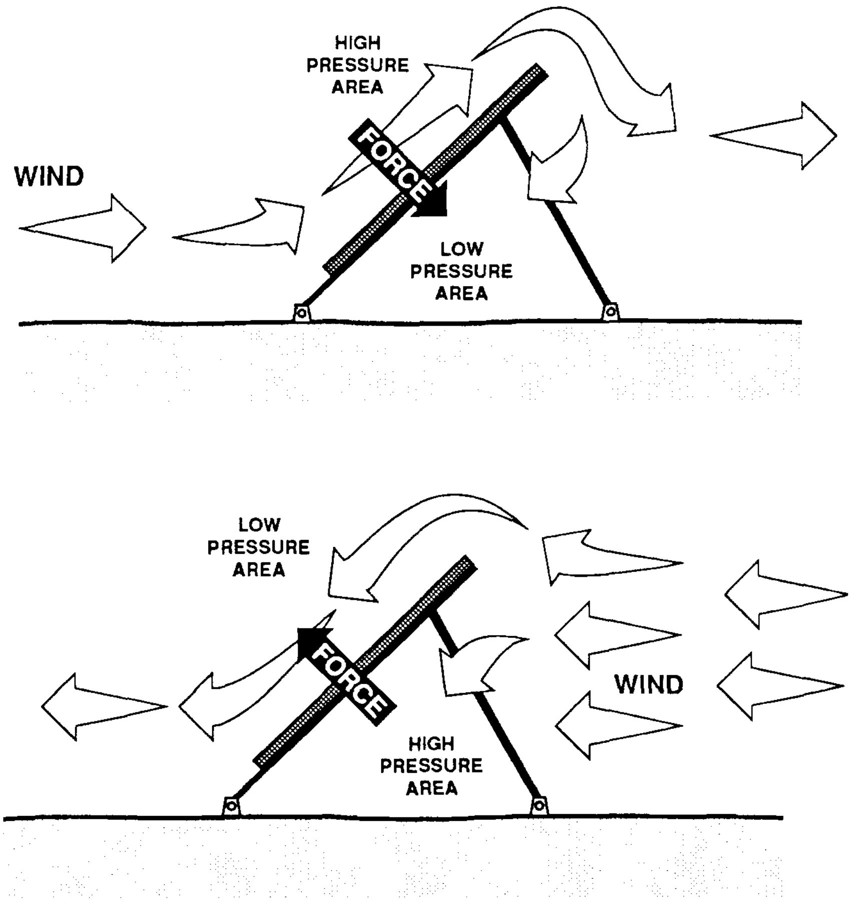


FIGURE 2-39
Forces on a
Photovoltaic Array

Structure mounting

Photovoltaic modules mounted on buildings or other structures are subjected to downward force when the wind hits their front surfaces. When the wind strikes the back of the modules, upward force is generated (Figure 2-39).

For this reason, the attachment to the building of modules with exposed backs is designed to resist both directions of force.

Another consideration when modules are mounted to a structure is the trapped heat between the module and the structure. Remember that module voltage drops with increased temperature.

Generally, photovoltaic arrays are mounted on structures in such a way that air can naturally circulate under the modules. This keeps the modules operating at the lowest possible temperature and highest possible output voltage. Access to the back of the modules also simplifies service operations.

2.3.5 Module Tilt and Orientation. Permanently mounted modules should be tilted up from the horizontal (Figure 2-40 and Table 2-2). The correct tilt angle varies with the times of year the system is used, and the latitude of the site. The tilt angle is measured from the horizontal, not from a pitched roof or hillside.

The tilt should be within 10 degrees of the listed angle. For example, a system used throughout the year at a latitude of 35° can have a tilt angle of 25° to 45° without a noticeable decrease in annual performance.

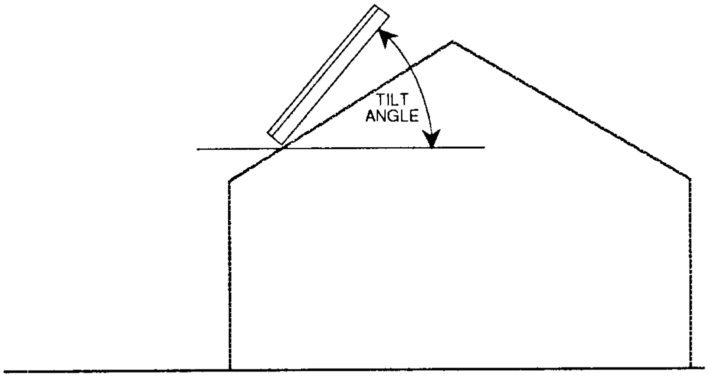


FIGURE 2-40
Module Tilt Measured from the Horizontal on Level and Tilted Surfaces

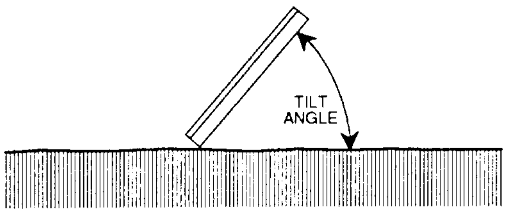


TABLE 2-2: Photovoltaic Module Tilt Angles

Time of Year System is Used the Most	Recommended Tilt Angle
All Year	Latitude
Mostly Winter	Latitude + 15°
Mostly Summer	Latitude - 15°
Mostly Fall or Spring	Latitude

For proper operation, the modules must be oriented as close as possible toward the equator. In the Northern Hemisphere, this direction is true south. In most areas, this varies from the magnetic south given by a compass. A simple correction must be made.

First, find the magnetic variation from an isogonic map. This is given in degrees east or west from magnetic south (Figure 2-41).

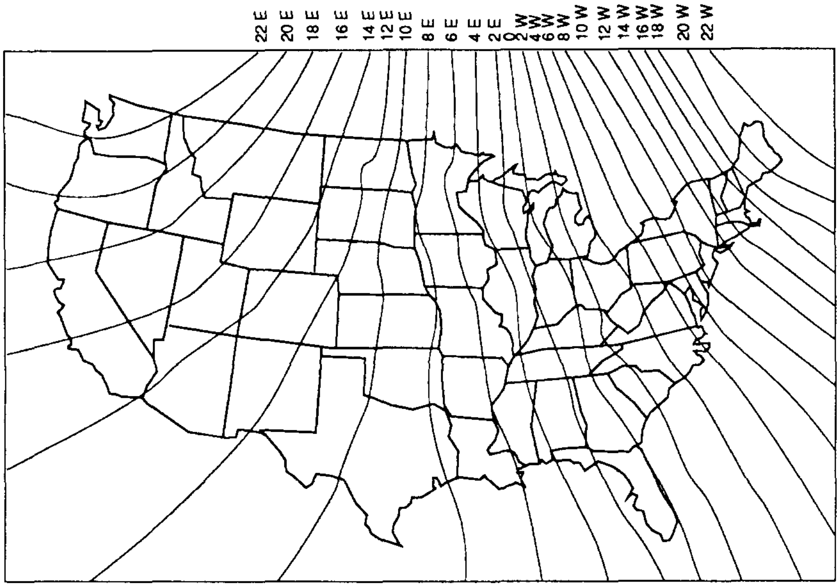


FIGURE 2-41
Isogonic Map of the United States

For example, a site in Montana has a magnetic variation of 20° east. This means that true south is 20° east of magnetic south. On a compass oriented so the north needle is at 360°, true south is in the direction indicated by 160° (Figure 2-42).

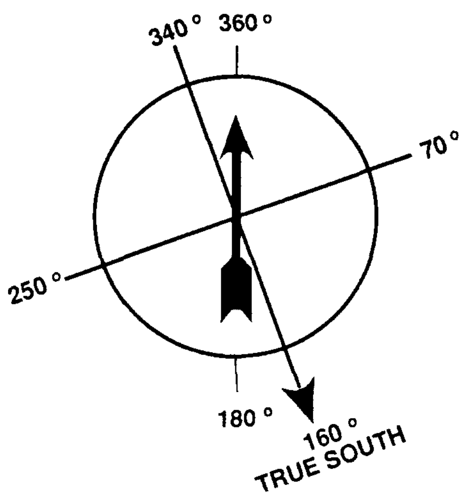


FIGURE 2-42
Directions on a Compass at 20° East Magnetic Variation

The modules should be installed within 20° of true south. In areas with morning fog, the array can be oriented up to 20° toward the west to compensate. Conversely, arrays in areas with a high incidence of afternoon storms can be oriented toward the east.

If the array is located in the Southern Hemisphere, the array must face true north.

Small portable arrays are usually just pointed at the sun, and moved every hour or so to follow the sun across the sky.

2.4 TYPICAL APPLICATIONS

2.4.1 DC Loads.

Effect of loads on the system

Loads directly influence the performance of the entire photovoltaic system. Oversize or extra loads can cause a system to fail if the loads require more power than the modules can generate or than the battery can store.

Likewise, the efficiency of the load influences the photovoltaic system's performance. All loads should be as efficient as possible.

Lighting and other resistive loads

Incandescent or quartz halogen lighting for general purposes, security, or navigational aids is available in DC versions, and can be supplied with power by a photovoltaic system.

Timers, motion detectors, or photocells (to determine dusk and dawn) should be used whenever possible, to eliminate leaving the lights on when they are not needed.

The lamp, fixture, and general system design should be as efficient as possible. The use of DC lighting equipment is a good way to avoid the inefficiencies of the inverter needed to convert DC to AC. DC fluorescent and low pressure sodium systems are available, are much more efficient, and are discussed below under inductive loads.

"Heating" loads are a poor use of PV generated electricity. These include resistive heating appliances and tools such as toasters, coffee makers, soldering irons, space and water heaters.

Because of the high amount of energy they consume, these loads should be used only when there is no other option, or if the load will only be used occasionally. Oversized or inappropriate loads often result in system failure.

Inductive loads

Inductive loads are those involving a motor or an electromagnet. Many photovoltaic systems supply energy to DC motors driving power tools, fans, pumps, and appliances.

Inductive loads also include solenoids, which use electricity to create a magnetic field to open or close valves or perform other operations in a variety of mechanical systems.

Again, the efficiency of the load should be as high as possible. One advantage to DC motors is that they are more efficient than AC motors.

DC lighting systems using a ballast, such as low pressure sodium and fluorescent systems, are also inductive loads (Figure 2-43). They should be used whenever possible, as they are considerably more efficient than incandescent or quartz halogen systems.

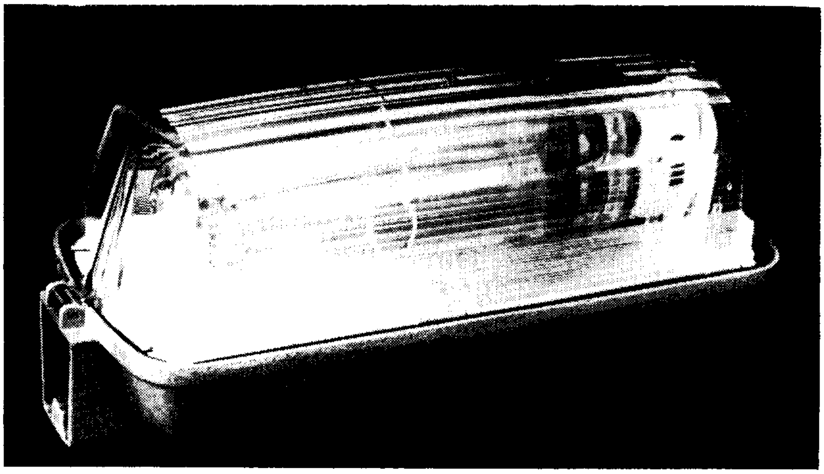


FIGURE 2-43
Low Pressure Sodium Light

Photo Courtesy of Thin-Lite Corp.

Electronic loads

A wide variety of communications, data gathering, security, and other equipment operates on DC normally. These can be operated by photovoltaic systems. Again, the loads should not be operated unless they are needed.

Many of these loads are sensitive to small variations in voltage. They usually are operated on photovoltaic systems with batteries, rather than direct systems.

Battery charging

Almost all of these loads can be operated directly from the photovoltaic array or from batteries charged by the array. Therefore, battery charging is an important DC application.

Photovoltaic systems are popular for the recharging or maintenance of charge in vehicle batteries, particularly when the vehicle is unused for long periods of time.

2.4.2 AC Loads.

AC loads can be used if the photovoltaic system includes an inverter. In general, it is best to try to limit AC loads because of the energy lost in the conversion of DC to AC in an inverter. Inverters are discussed in detail in Section 2.5.3.

Lighting and other resistive loads

Sometimes, the availability of AC power makes the use of small amounts of AC incandescent lighting reasonably appropriate. With photovoltaic systems, incandescent lighting should be minimized because of its poor efficiency. AC fluorescent and low pressure sodium lighting systems are more efficient. Using DC power directly from the battery to operate DC versions of these lighting systems is an even better choice.

The use of AC appliances and tools such as toasters, dryers, soldering irons, and heat guns (which are primarily resistance heaters) should be minimized.

Inductive loads

Many appliances and power tools are only available with AC motors. These motors generally require a "clean" source of AC power, and thus a more sophisticated inverter. More information on inverters can be found in Section 2.5.3.

Motors operating on a power source which is not clean enough will waste electrical energy. The wasted energy is dissipated through the motor as heat. This can shorten the lifetime of the motor.

Combination 120V AC/DC motors are available which can operate on either power source. These can be used as a portable DC device in the field with a photovoltaic system, and "plugged in" to a utility's AC supply at other times. It should be noted, however, that the majority of the DC systems installed are rarely 120 volts.

Microwave ovens require a fairly clean AC power supply, and are an inductive load. The power supply requires the peak voltage of a sine wave (clean power to operate properly).

For lighting, high pressure sodium lighting systems offer the most efficiency, followed in order by low pressure sodium, metal halide, mercury vapor, and fluorescent. For indoor lighting, fluorescent is probably the best choice, since the others supply light with poor color rendering.

Electronic loads

Some electronic devices, including communications devices and small computers, will operate satisfactorily on the output of simple inverters. Other devices, such as video and audio equipment, require the cleaner output of more sophisticated inverters. Again, more information on inverters can be found in Section 2.5.3.

A good example of the difficulty of categorizing electronic loads is a personal computer. The computer itself may run without any problems on the output of a simple inverter. The video monitor and printer, however, will not. Therefore, the entire package should be run with the cleaner power supply of a more sophisticated inverter. Clocks may run fast on an inverter that produces a square or quai-sine wave.

Another way to categorize electronic loads is their sensitivity to RFI (Radio Frequency Interference) or EMI (ElectroMagnetic Interference). Simpler inverters can create significant RFI or EMI "noise," which may interfere with the operation of some equipment. This is particularly true of two-way communication equipment, televisions, and radios.

2.5 SYSTEM COMPONENT OPERATION

2.5.1 Battery and Other Storage. Batteries store the electrical energy generated by the modules during sunny periods, and deliver it whenever the modules cannot supply power.

Normally, batteries are discharged during the night or cloudy weather. But if the load exceeds the array output during the day, the batteries can supplement the energy supplied by the modules.

The interval which includes one period of charging and one of discharging is described as a "cycle." Ideally, the batteries are recharged to 100% capacity during the charging phase of each cycle. The batteries must not be completely discharged during each cycle.

No single component in a photovoltaic system is more affected by the size and usage of the load than storage batteries. If a charge controller is not included in the system, oversized loads or excessive use can drain the batteries' charge to the point where they are damaged and must be replaced. If a controller does not stop overcharging, the batteries can be damaged during times of low or no load usage or long peroids of full sun.

For these reasons, battery systems must be sized to match the load. In addition, different types and brands of batteries have different "voltage setpoint windows." This refers to the range of voltage the battery has available between a fully discharged and fully charged state.

As an example, a battery may have a voltage of 14 volts when fully charged, and 11 when fully discharged. Assume the load will not operate properly below 12 volts. Therefore, there will be times when this battery cannot supply enough voltage for the load. The battery's voltage window does not match that of the load.

Performance

The performance of storage batteries is described two ways. These are (1) the amp-hour capacity, and (2) the depth of cycling.

Amp-hour capacity

The first method, the number of amp-hours a battery can deliver, is simply the number of amps of current it can discharge, multiplied by the number of hours it can deliver that current.

System designers use amp-hour specifications to determine how long the system will operate without any significant amount of sunlight to recharge the batteries. This measure of "days of autonomy" is an important part of design procedures.

Theoretically, a 200 amp-hour battery should be able to deliver either 200 amps for one hour, 50 amps for 4 hours, 4 amps for 50 hours, or one amp for 200 hours.

This is not really the case, since some batteries, such as automotive ones, are designed for short periods of rapid discharge without damage. However, they are not designed for long time periods of low discharge. This is why automotive batteries are not appropriate for, and should not be used in, photovoltaic systems.

Other types of batteries are designed for very low rates of discharge over long periods of time. These are appropriate for photovoltaic applications. The different types are described later.

Charge and discharge rates

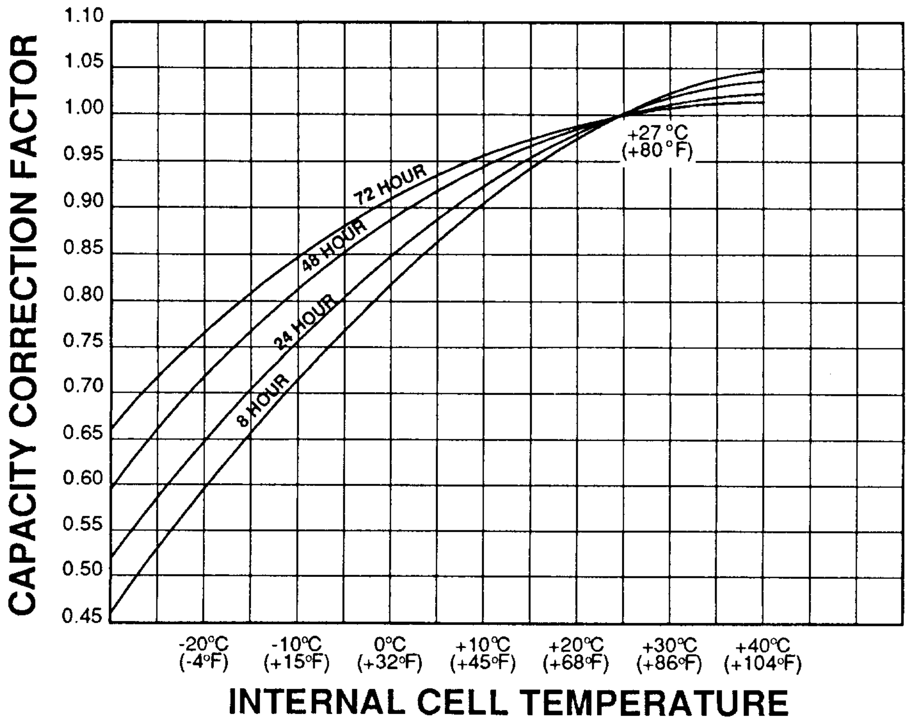
If the battery is charged or discharged at a different rate than specified, the available amp-hour capacity will increase or decrease. Generally, if the battery is discharged at a slower rate, its capacity will probably be slightly higher. More rapid rates will generally reduce the available capacity.

The rate of charge or discharge is defined as the total capacity divided by some number. For example, a discharge rate of C/20 means the battery is being discharged at a current equal to 1/20th of its total capacity. In the case of a 400 amp-hour battery, this would mean a discharge rate of 20 amps.

Temperature

Another factor influencing amp-hour capacity is the temperature of the battery and its surroundings. Batteries are rated for performance at 80°F. Lower temperatures reduce amp-hour capacity significantly. Higher temperatures result in a slightly higher capacity, but this will increase water loss and decrease the number of cycles in the battery life (Figure 2-44).

FIGURE 2-44
Battery Capacity at Different Temperatures



Depth of discharge

The second description of performance is depth of discharge. This describes how much of the total amp-hour capacity of the battery is used during a charge-recharge cycle.

As an example, "shallow cycle" batteries are designed to discharge from 10% to 25% of their total amp-hour capacity during each cycle. In contrast, most "deep cycle" batteries designed for photovoltaic applications are designed to discharge up to 80% of their capacity without damage. Manufacturers of deep cycle "Ni cad" batteries claim their product can be totally discharged without damage.

Even deep cycle batteries are affected by the depth of discharge. The deeper the discharge, the smaller the number of charging cycles the battery will last (Figure 2-45). They are also affected by the rate of discharge and their temperature.

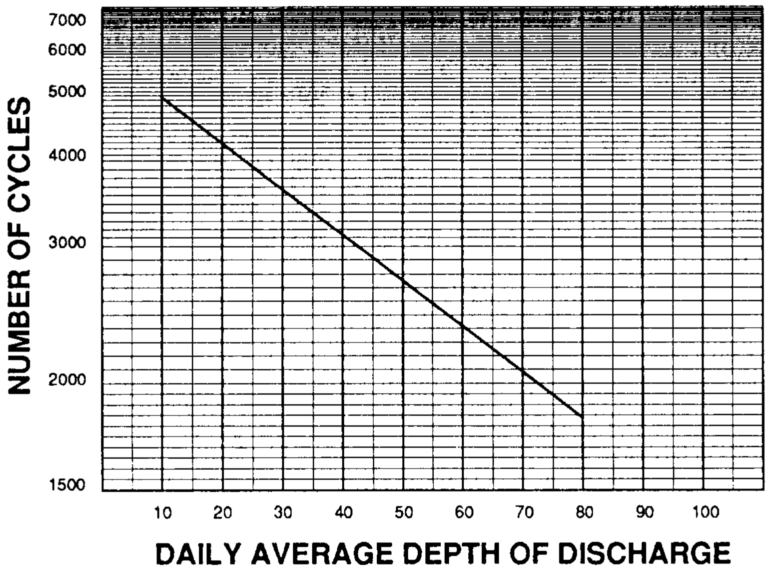


FIGURE 2-45
Number of Cycles for Different Discharge Depths

Vented lead acid batteries

Although automotive batteries are not appropriate for photovoltaic applications, deep cycle lead acid batteries similar to automotive types, are referred to as marine type batteries and are used more often.

These batteries are true deep cycle units. They can be discharged as much as 80%, although less discharge depth will result in more charge cycles and thus a longer battery life.

Internal construction

These batteries are made up of lead plates in a solution of sulfuric acid. The plates are a lead alloy grid with lead oxide paste dried on the grid. The sulfuric acid and water solution is normally called "electrolyte."

The grid material is an alloy of lead because pure lead is a physically weak material. Pure lead would break during transportation and service operations involving moving the battery.

The lead alloy is normally lead with 2-6% antimony. The lower the antimony content, the less resistant the battery will be to charging. Less antimony also reduces the production of hydrogen and oxygen gas during charging, thereby reducing water consumption. On the other hand, more antimony allows deeper discharging without damage to the plates. This in turn means longer battery life. Lead-antimony batteries are deep cycle types.

Cadmium and strontium are used in place of antimony to strengthen the grid. These offer the same benefits and drawbacks as antimony, but also reduce the amount of self-discharge the battery has when it is not being used.

Calcium also strengthens the grid and reduces self-discharge. However, calcium reduces the recommended discharge depth to no more than 25%. Therefore, lead-calcium batteries are shallow cycle types.

Both positive and negative plates are immersed into a solution of sulfuric acid and subjected to a "forming" charge by the manufacturer. The direction of this charge causes the paste on the positive grid plates to convert to lead dioxide. The negative plates' paste converts to "sponge" lead. Both materials are highly porous, allowing the sulfuric acid solution to freely penetrate the plates.

The plates are alternated in the battery, with separators between each plate. The separators are made of porous material to allow the flow of electrolyte. They are electrically non-conductive. Typical materials include mixtures of silica and plastics or rubber. (Originally, spacers were made of thin sheets of cedar.)

Separators are either individual sheets or "envelopes." Envelopes are sleeves, open at the top, which are put on only the positive plates.

A group of negative and positive plates, with separators, makes up an "element" (Figure 2-46). An element in a container immersed in electrolyte makes up a battery "cell."

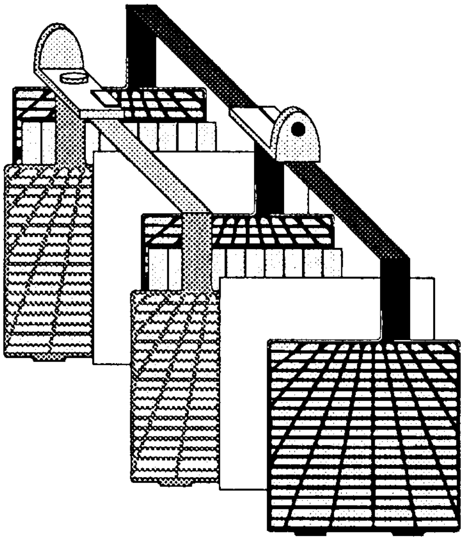


FIGURE 2-46
Element Construction
of a Lead Acid Battery

Larger plates, or more of them, will increase the amp-hours the battery can deliver. Thicker plates, or less plate count per cell, will allow a greater number of cycles and longer lifetime from the battery (Figure 2-47).

Regardless of the size of the plates, a cell will only deliver a nominal 2 volts. Therefore, a battery is typically made up of several cells connected in series, internally or externally, to increase the voltage the entire battery can deliver.

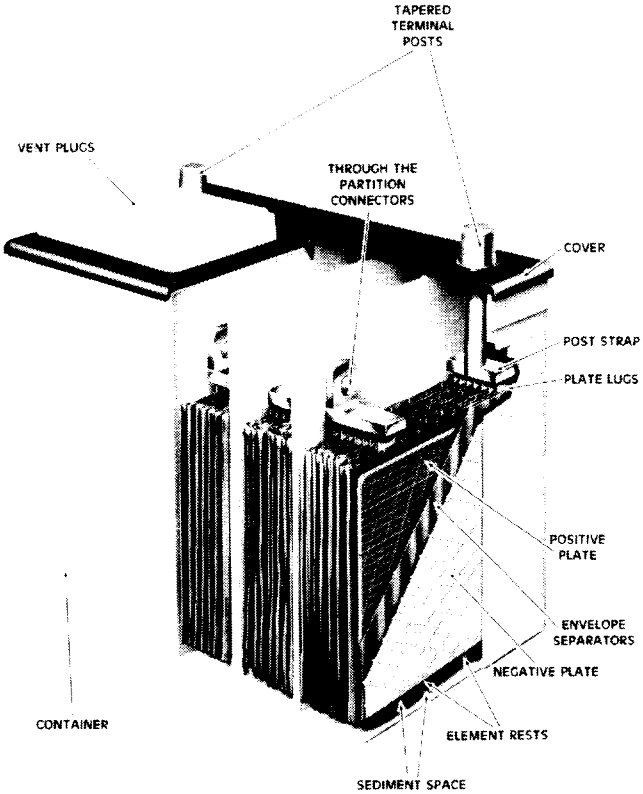


FIGURE 2-47
Complete Battery
Construction

Photo Courtesy of Battery Council International

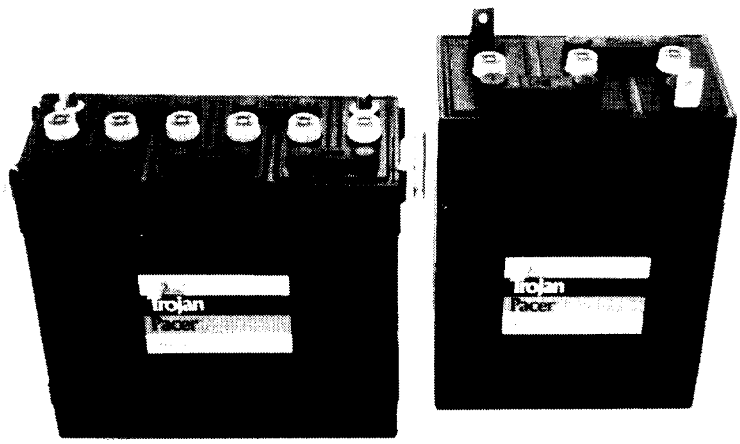
This is why a six volt battery has three cells, and 12 volt batteries have six (See Figure 2-48). Some batteries used in photovoltaic systems have only one cell, allowing the user to have any number of volts in the battery system, as long as it is a multiple of two.

Terminals

The internal straps which make these internal connections are brought up to the top of the battery and connected to the external terminals. The most familiar terminal is the tapered top type. The taper allows for a wide variety of cable clamp sizes. The positive terminal is slightly larger than the negative one to reduce the chance of accidentally switching the cables. Figure 2-48 shows a variety of battery terminals. Other terminal types used more often in photovoltaic battery applications include "L" terminals, wing-nut terminals, and "universal" terminals. The type of terminal used may depend on the number and type of interconnections between the batteries and the balance of the system.

FIGURE 2-48
Various Battery
Terminals

Photo Courtesy of Trojan Battery Co.



Interconnections can be made with short cables, #2 AWG or larger. The cables end in appropriate terminals. They can also be made with bus bars made specifically for this purpose by the battery manufacturer.

Venting

The cells of a vented lead acid battery are vented to allow the hydrogen and oxygen gas to escape during charging, and to provide an opening for adding water lost during gas production. Section 3.1.7 provides more information on battery venting requirements.

Although open caps are most common, the caps may be a flame arrester type, which prevents a flame from outside the battery from entering the cell.

"Recombinant" type caps are also available. These contain a catalyst that causes the hydrogen and oxygen gases to recombine into water, significantly reducing the water requirements of the battery.

WARNING!

Never smoke or have open flames or sparks around batteries! As the batteries charge, explosive hydrogen gas is produced.

Always make sure battery banks are adequately vented and that a No Smoking sign is posted in a highly visible place.

Sulfation

If a lead acid battery is left in a deeply discharged condition for a long period of time, it will become "sulfated". Some of the sulfur in the acid will combine with lead from the plates to form lead sulfate. If the battery is not refilled with water periodically, part of the plates will be exposed to air, and this process will be accelerated.

Lead sulfate coats the plates so the electrolyte cannot contact it. Even the addition of new water will not reverse the permanent loss in battery capacity.

Treeing

Treeing is a short circuit between positive and negative plates caused by misalignment of the plates and separators. The problem is usually caused by a manufacturing defect, although rough handling is another cause.

Mossing

Mossing is a build-up of material on top of the battery elements. Circulating electrolyte brings small particles to the top of the battery where they are caught on the element tops. Mossing causes shorts between negative and positive plates. Heavy mossing causes a short between the element plates and the plate strap above them.

To avoid mossing, the battery should not be subjected to continuous overcharging or rough handling.

State of charge, specific gravity, and voltage

The percentage of acid in the electrolyte is measured by the "specific gravity" of the fluid. This measures how much the electrolyte weighs compared to an equal quantity of water. Specific gravity is measured with a hydrometer.

The greater the state of charge, the higher the specific gravity of the electrolyte. The voltage of each cell, and thus the entire battery, is also higher. Measuring specific gravity during the discharge of a battery will be a good indicator of the state of the charge. During the charging of a flooded battery, the specific gravity will lag the state of charge because complete mixing of the electrolyte does not occur until gassing commences near the end of charge. Because of the uncertainty of the level of mixing of the electrolyte, this measurement on a fully charged battery is a better indicator of the health of the cell. Therefore, this should not be considered an absolute measurement for capacity and should be combined with other techniques. (Figure 2-49).

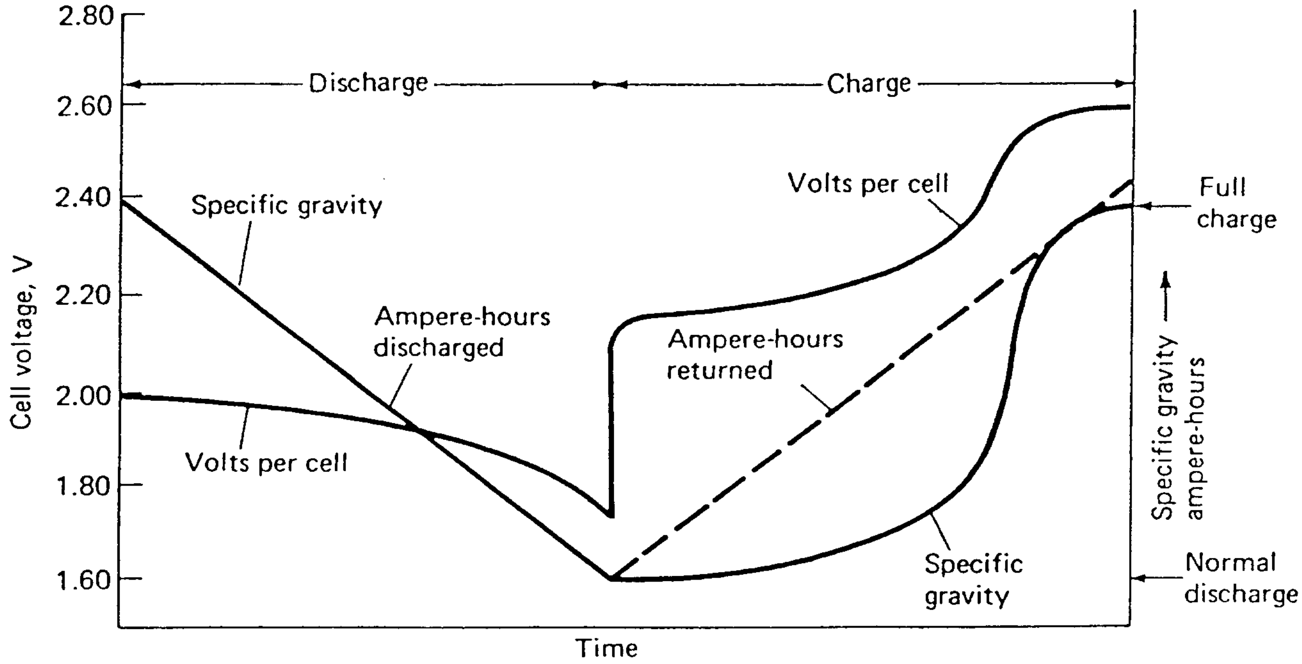


Figure 2-49 Typical Voltage and Specific Gravity Characteristics of a Lead-acid Cell (constant-rate discharge and charge).

Freezing point

Since lead acid batteries use an electrolyte which is partially water, they can freeze. The sulfuric acid in a battery acts as an antifreeze, however. The higher the percentage of acid in the water, the lower the freezing temperature. However, even a fully charged lead acid battery will freeze at some extremely low temperature.

As Table 2-3 shows, at a 50% charge, a typical lead acid battery will freeze around -10°F. Notice that as the state of charge goes down, the specific gravity goes down as well. The acid is becoming weaker and weaker, and lighter and lighter, until it is only slightly denser than water.

> NOTE
>
> The information in Table 2-3 and Figures 2-50 and 2-51 is for deep cycle lead acid batteries. Shallow cycle automotive batteries have slightly different values.

As you can see, lead acid batteries should be kept above 20°F if they are ever allowed to be fully discharged. If they cannot be kept warmer than this, they should be maintained at a high enough charge to prevent freezing of the electrolyte.

This can be done automatically, with a charge controller capable of disconnecting the load when the battery voltage drops to a preset level. However, this method cannot be used if the load is critical and cannot be turned off.

TABLE 2-3: States of Charge, Specific Gravities, Voltages, and Freezing Points for Typical Deep Cycle Lead Acid Batteries

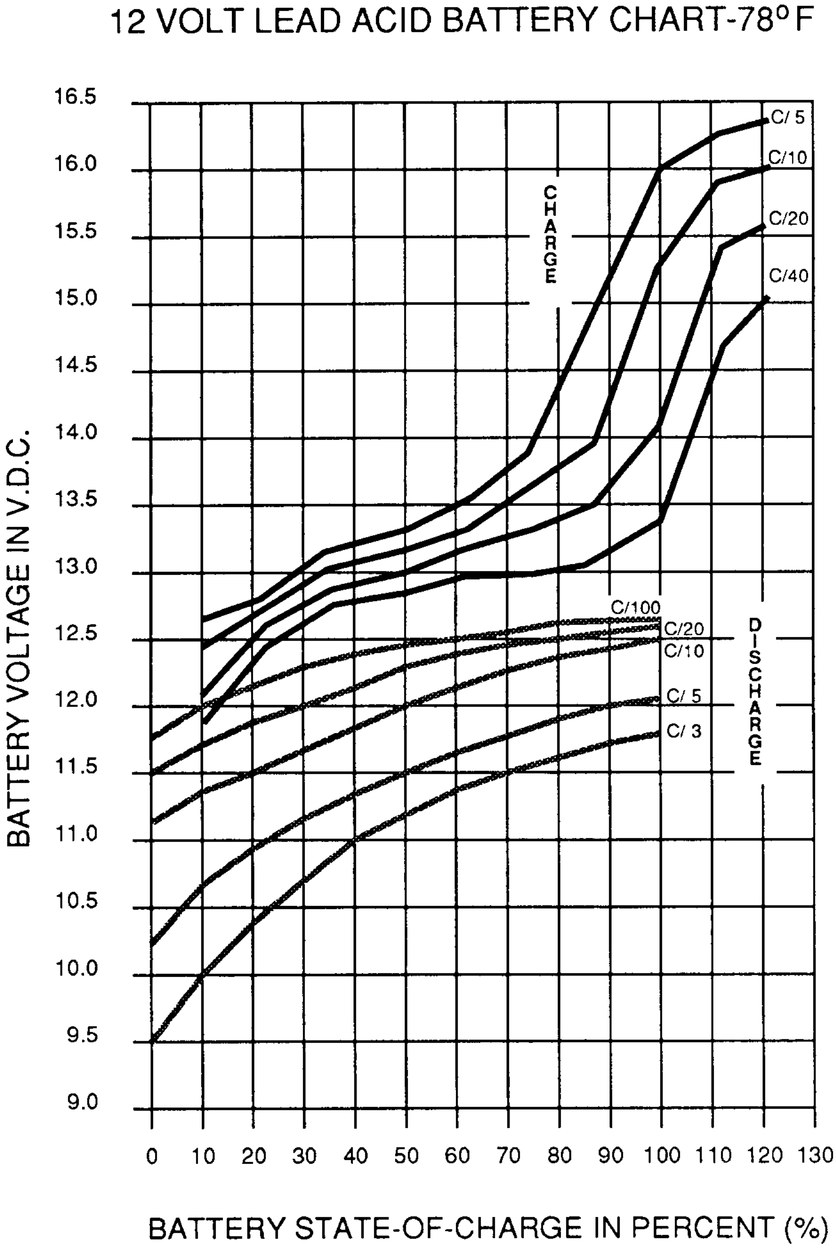
State of Charge	Specific Gravity	Voltage per Cell (volts)	Voltage of 12V (6 cell) Battery	Freezing Point (°F)
Fully charged	1.265	2.12	12.70	-71
75% charged	1.225	2.10	12.60	-35
50% charged	1.190	2.08	12.45	-10
25% charged	1.155	2.03	12.20	+3
Fully Discharged	1.120	1.95	11.70	+17

The charging characteristics of lead acid batteries changes with electrolyte temperature. The colder the battery, the lower the rate of charge it will accept. Higher temperatures allow higher charge rates.

If a battery will be used in a climate that will continuously be extremely hot or cold, with minimum temperature swings, it would be wise to adjust the electrolyte specific gravity for the temperature. This will help extend the life and enhance the performance of the battery under these extreme conditions. This adjustment should be done at the battery manufacturer, or through their supervision.

For example, a typical lead acid battery which is half charged will only accept two amps at 0°F. At 80°F, it will accept over 25 amps. This is why most charge controllers equipped with temperature compensation change their voltage settings with temperature. A few measure the battery temperature, and adjust the charging rate (current flow) accordingly.

A final characteristic of lead acid batteries is their fairly high rate of self-discharge. When not in service they may loose from 5% per month to 1% per day of their capacity, depending on temperature and cell chemistry. The higher the temperature, the faster the rate of self-discharge.



Courtesy of Home Power Magazine

FIGURE 2-50
Terminal Voltages and States of Charge for 12 Volt Lead Acid Batteries

Note: Divide these voltages by two for 6 volt batteries

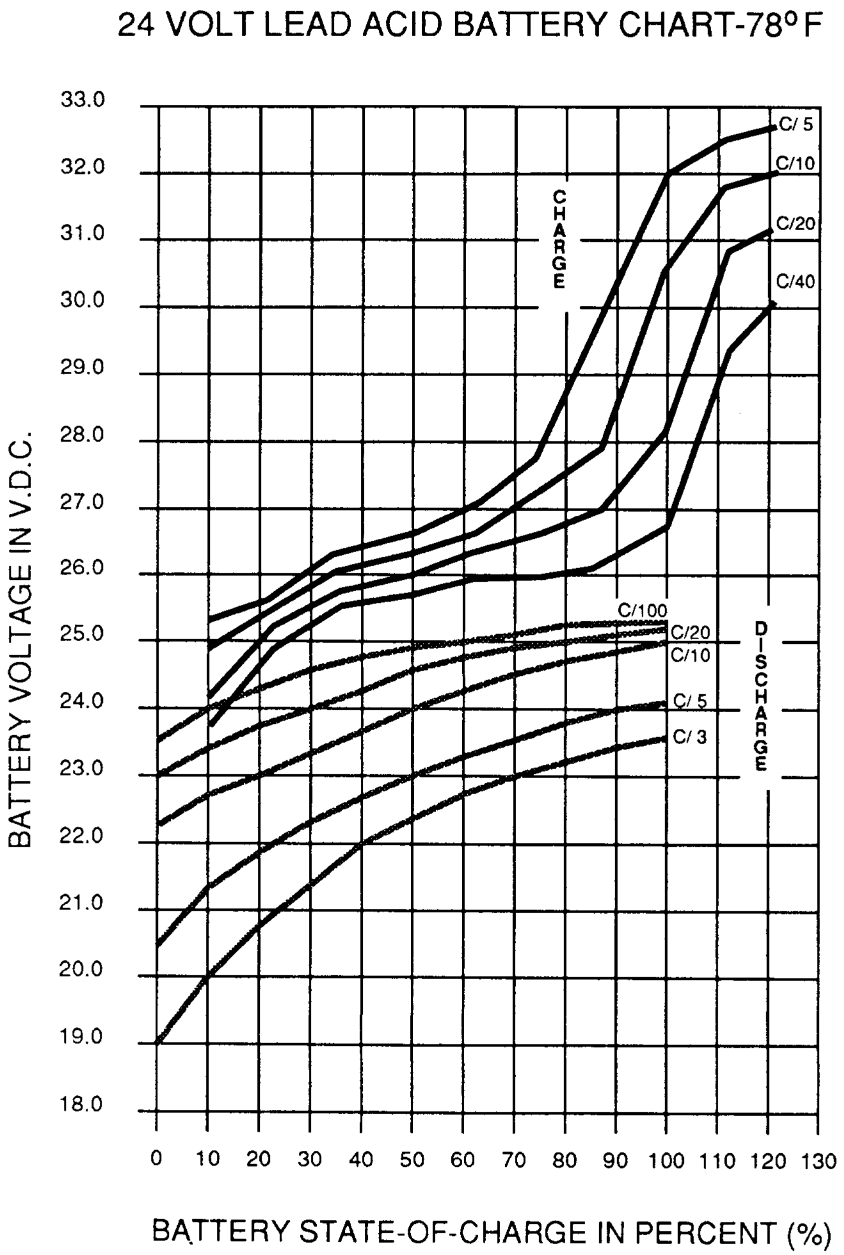


FIGURE 2-51
Terminal Voltages and States of Charge for 24 Volt Lead Acid Batteries

Courtesy of Home Power Magazine

Sealed flooded (wet) lead acid batteries

As described before, the use of less antimony, or using calcium, cadmium, or strontium in place of antimony, results in less gassing and lower water consumption. However, these batteries should not be discharged more than 15-25%, or the life of the battery will be dramatically shortened.

Self discharge is less of a factor with sealed lead acid batteries due to the fact that these batteries are typically lead-calcium or lead-calcium/antimony hybrids. Self discharge can be minimized by storing batteries in cool areas between 5-15°C.

The rate of water loss may be so low that the vent plugs for each cell can be nearly or completely sealed . In most of these batteries, there is still some production of hydrogen gas. Therefore, a venting system is still required, but it is typically a pressure valve regulated system.

The temperature range sealed batteries can accommodate is about the same as unsealed batteries. Since the specific gravity cannot be measured with a hydrometer, many sealed batteries have a built in hydrometer.

A built-in hydrometer is a captive float in the electrolyte. If the specific gravity is high enough, the float comes up against a window at the top of the battery. If the float is visible in the window, the battery is nearly fully charged. In PV systems, sometimes this float gets stuck and the battery should be lightly tapped to ensure free movement of the hydrometer.

If the battery is not fully charged, the float will sink, and cannot be seen in the window.

The charging characteristics of sealed lead acid batteries also changes with electrolyte temperature. Charge controllers used on these batteries should include temperature compensation for battery temperatures below 70°F.

Captive electrolyte batteries

Batteries with a gelled (Gel) or absorbed glass mat (AGM) electrolyte are available completely sealed (Figure 2.52). These batteries are sometimes referred to as "Valve Regulated Batteries." Some of the newer batteries have catalytic recombiners internal to their battery to aid in the reduction of water loss. All sealed batteries will vent if they are overcharged to the point of excessive gassing to prevent extreme pressures from building up in the battery case. This electrolyte is then lost forever and the life of the battery may be shortened. This problem can be reduced or eliminated by properly charging the battery as recommended by the manufacturer and by using temperature compensation in the charge controller.

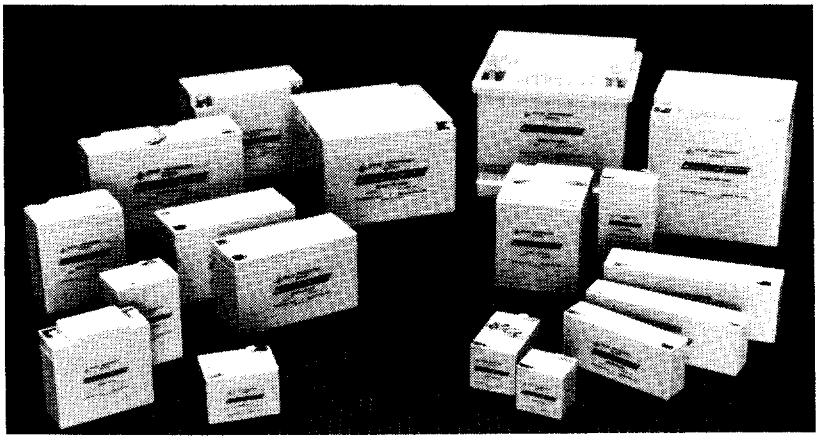


FIGURE 2-52
Sealed Lead Acid
Captive Electrolyte
Gelled Batteries

Photo Courtesy of Power-Sonic Corp.

This type of battery is generally a lead calcium or lead calcium/antimoninal hybrid. Because the electrolyte is captive, there is no need to charge the battery high enough to gas the electrolyte. The battery can be used in any position, even upside down. Since the electrolyte does not flow away from the plates, the battery still delivers full capacity. The manufacturer should be consulted for the proper regulation voltage for their specific battery.

These batteries are typically shallow cycle batteries. Discharging these batteries greater than 20% will significantly reduce the lifetime of the battery.(Figures 2-53 and 2-54).

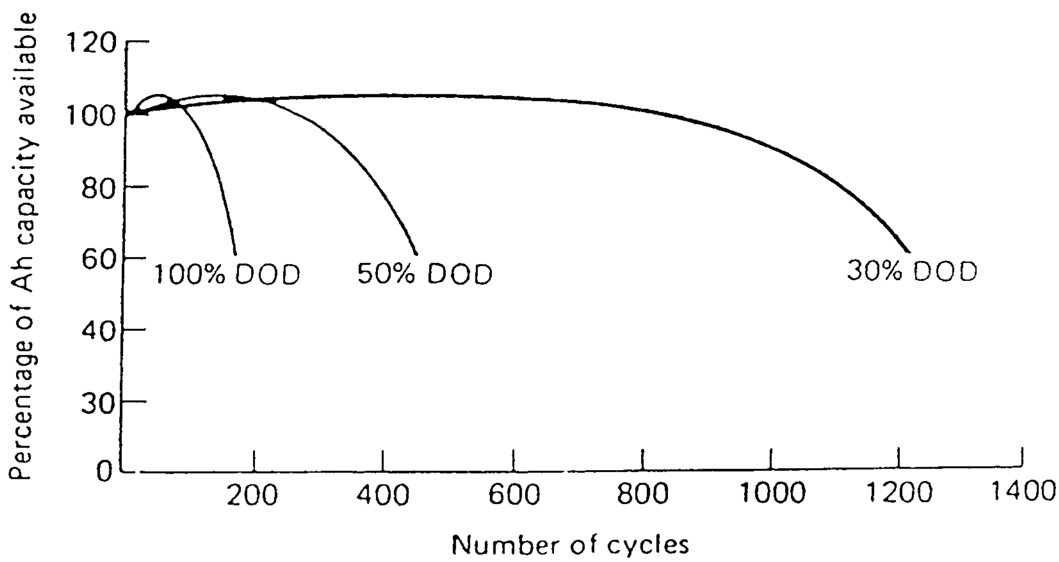


Figure 2-53 Cycle Service Life of a Gel Cell Lead-Acid Battery in Relation to Depth of Discharge (20°C)

Linden, Handbook of Batteries

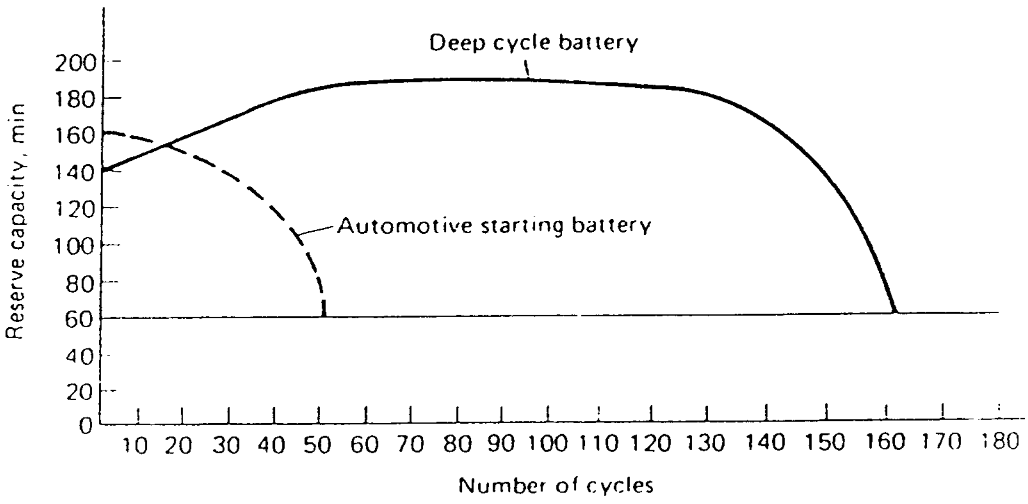


Figure 2-54 Cycle Life Characteristics at a Low Discharge Rate (25A)

GNB Batteries, St. Paul Minnesota

These batteries have shown some temperature limitations, typically ranges in excess of -20 to +50 degrees C should be avoided. Self discharge rates are very low, comparable to lead calcium batteries or better.

Nickel cadmium (Ni cad) batteries

Ni cad batteries have a physical structure similar to lead acid batteries. Instead of lead plates, they use nickel hydroxide for the positive plates and cadmium oxide for the negative plates. The electrolyte is potassium hydroxide.

The cell voltage of a typical Ni cad battery is 1.2 volts, rather than the two volts per cell of a lead battery (Figure 2-55).

Ni cad batteries can survive freezing and thawing without any effect on performance. High temperatures have less of an effect than they have on lead acid batteries. Self-discharge rates range from 3-6% per month.

Ni cad batteries are less affected by overcharging. They can be totally discharged without damage. They are not subject to sulfation. Their ability to accept charging is independent of temperature.

Although the initial cost of Ni cad batteries is higher than lead acid types, their lower maintenance costs and longer lives make them a logical choice for many photovoltaic installations. This is particularly true if the system is in a remote or dangerous location.

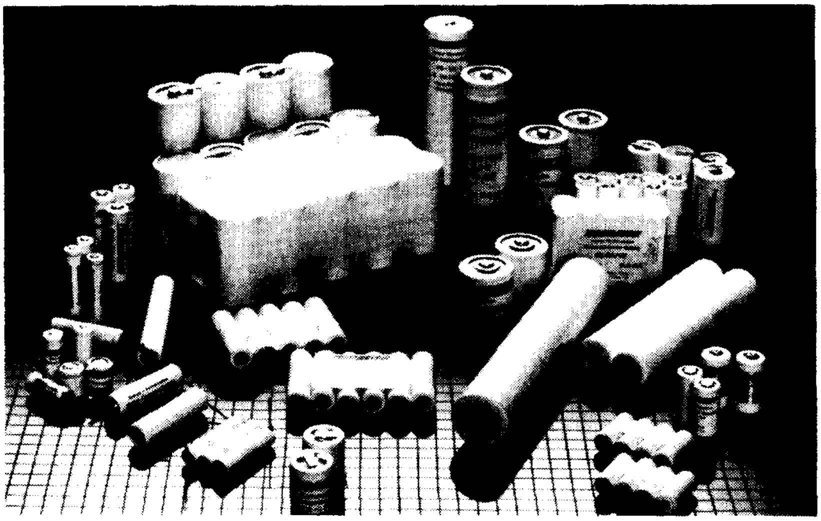


FIGURE 2-55
Ni Cad Batteries

Photo Courtesy of Power-Sonic Corp.

Since battery maintenance is a major part of all photovoltaic system maintenance, significant reductions in service time and costs can be achieved.

However, Ni cad batteries cannot be tested as accurately as a "wet" lead-acid battery. If state of charge monitoring is necessary, Ni cad may not be the best choice.

Future prospects for batteries

An electrical storage method now being developed is a redox battery. Redox is short for reduction-oxidation, which is a cycle of chemical reactions.

This battery uses two chemicals, chromium chloride and iron chloride, which are pumped through a stack of cells with electrodes. A special membrane keeps the fluids physically separated, but allows electrical energy to move between them and the electrodes.

Another battery being tested uses nickel and iron instead of lead oxides.

A battery being investigated for electric vehicles is the lithium-metal sulfide type. This battery uses lithium, alloyed with aluminum, for the negative electrodes, iron sulfide for the positive electrodes, and magnesium oxide for the separators.

The lithium-metal sulfide battery operates at a temperature of almost 850°F. It requires a special container to maintain that temperature.

A polymer battery is being developed which uses no liquid or dangerous materials, and can be molded into any shape. It is not expected to be available until at least 1995.

Batteries in series and parallel

Batteries, like photovoltaic cells, can be connected in series to increase the voltage. They can be connected in parallel to increase the amp-hour capacity of the battery system. Interconnected groups of batteries are usually called "battery banks" (Figure 2-56).

Connecting batteries in both series and parallel will increase the voltage and the amp-hour capacity.

The connections and wiring of the batteries plays a large role in how well the batteries are treated. The quality and method of wiring these systems is very important to maintain acceptable battery health and lifetime. A large voltage drop in the system between the battery and the battery charge controller will change how the battery charge controller operates. This voltage drop, measured during full charging rates, will reduce the voltage regulation setpoint the battery is charged to and reduce the capacity and lifetime of the battery.

Fuses and switches, if not properly chosen, can develop a large voltage drop and can develop into a problem area. Attention should be paid to using "DC Rated" fuses and switches to reduce system problems.

When paralleling batteries, it is best to reduce the effects of voltage drops (unequal resistances) between parallel branches. This will allow all of the batteries in the system to operate at an equal voltage and current level.

The best method is to ensure that the battery cable to the parallel battery is sized to reduce the voltage drop to a minimum during peak current demand in the system. This is calculated by using the maximum charging or load currents mutilplied by the resistance of the wire. Multistrand welding cable is typically used.

The other method is to use the same length of cable from each battery terminal to a central junction point. The positive and negative do not necessarily have to be the same length. This eliminates the uneven voltage drop between batteries and permits each battery to perform equally during peak current demand. This method allows you to use a smaller size battery cable.

A split bolt is the best way to connect multiple wires, covered with waterproof electrical tape. Wire nuts are not recommended for any connections within the system. When possible, a soldered connection will provide the best system performance and reliability.

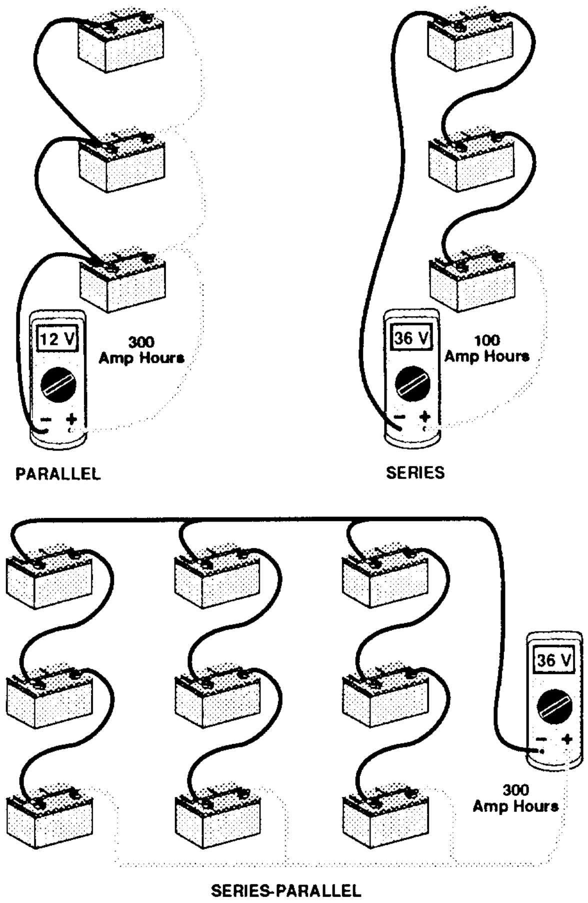


FIGURE 2-56
Batteries Connected in Series, Parallel, and Series-Parallel

WARNING!

Even when only partially charged, an interconnected battery bank can deliver enough voltage and current to arc weld! Always be careful around battery banks. Never allow tools to fall onto the terminals or connections. Never allow the construction or use of shelves above the batteries, as objects can fall off the shelves onto the batteries. Battery banks must always be adequately vented.

Table 2-4 summarizes the characteristics of the various types of batteries.

TABLE 2-4: Summary of Battery Characteristics

	Lead acid, unsealed, flooded (deep cycle)	Lead acid, sealed, flooded (shallow cycle)	Captive electrolyte (gelled cell or AGM)	Ni cad
Depth of Discharge	40-80%	15-25%	15-25%	100%
Self-discharge rate, %/month	5%	1-4%	2-3%	3-6%
Typical capacity, Amp-hours/ft.^{3}	1000	700	250	500
Range of capacities Amp-hrs/ft.^{3}	200 to 1425	164 to 1389	104 to 464	103 to 990
Typical capacity, Amp-hrs/lb.	5.5	4.6	2.2	5.0
Range of capacities, Amp-hrs/lb.	1.9 to 12.1	1.1 to 9.2	1.0 to 6.3	1.2 to 9.5
Minimum Environment Temperature (°F)	+20	+20	0	-50

Other storage methods

Some photovoltaic systems are only used for pumping water. If the water is pumped into a storage tank for later use, battery storage is unnecessary.

Similarly, a refrigerator with a freezer may be able to "coast" by making ice in the freezer during sunny times and letting it melt at night or during cloudy weather.

2.5.2 Charge Controllers.

The primary function of a charge controller in a stand-alone PV system is to protect the battery from overcharge and overdischarge. Any system that has unpredictable loads, user intervention, optimized or undersized battery storage (to minimize initial cost), or any characteristics that would allow excessive battery overcharging or overdischarging requires a charge controller and/or low-voltage load disconnect. Lack of a controller may result in shortened battery lifetime and decreased load availability (Reference 1).

Systems with small, predictable, and continuous loads may be designed to operate without a battery charge controller. If system designs incorporate oversized battery storage and battery charging currents are limited to safe finishing charge rates (C/50 flooded or C/100 sealed) at an appropriate voltage for the battery technology, a charge controller may not be required in the PV system (See references 2,3,4, and 5).

Proper operation of a charge controller should prevent overcharge or overdischarge of a battery regardless of the system sizing/design and seasonal changes in the load profile and operating temperatures. The algorithm or control strategy of a battery charge controller determines the effectiveness of battery charging and PV array utilization, and ultimately the ability of the system to meet the load demands. Additional features such as temperature compensation, alarms, and special algorithms can enhance the ability of a charge controller to maintain the health, maximize capacity, and extend the lifetime of a battery.

Basics of charge controller theory

While the specific control method and algorithm vary among charge controllers, all have basic parameters and characteristics. Manufacturer's data generally provides the limits of controller application such as PV and load currents, operating temperatures, losses, setpoints, and setpoint hysteresis values. In some cases the setpoints may be intentionally dependent upon the temperature of the battery and/or controller, and the magnitude of the battery current. A discussion of the four basic charge controller setpoints follows:

Regulation setpoint (VR): This setpoint is the maximum voltage a controller allows the battery to reach. At this point a controller will either discontinue battery charging or begin to regulate the amount of current delivered to the battery. Proper selection of this setpoint depends on the specific battery chemistry and operating temperature.

Regulation hysteresis (VRH): The setpoint is voltage span or difference between the VR setpoint and the voltage when the full array current is reapplied. The greater this voltage span, the longer the array current is interrupted from charging the battery. If the VRH is too small, then the control element will oscillate, inducing noise and possibly harming the switching element. The VRH is an important factor in determining the charging effectiveness of a controller.

Low voltage disconnect (LVD): The setpoint is voltage at which the load is disconnected from the battery to prevent overdischarge. The LVD defines the actual allowable maximum depth-of-discharge and available capacity of the battery. The available capacity must be carefully estimated in the system design and sizing process. Typically, the LVD does not need to be temperature compensated unless the batteries operate below 0°C on a frequent basis. The proper LVD setpoint will maintain good battery health while providing the maximum available battery capacity to the system.

Low voltage disconnect hysteresis (LVDH): This setpoint is the voltage span or difference between the LVD setpoint and the voltage at which the load is reconnected to the battery. If the LVDH is too small, the load may cycle on and off rapidly at low battery state-of-charge, possibly damaging the load and/or controller. If the LVDH is too large, the load may remain off for extended periods until the array fully recharges the battery. With a large LVDH, battery health may be improved due to reduced battery cycling, but this will reduce load availability. The proper LVDH selection will depend on the battery chemistry, battery capacity, and PV and load currents.

Charge controller algorithms

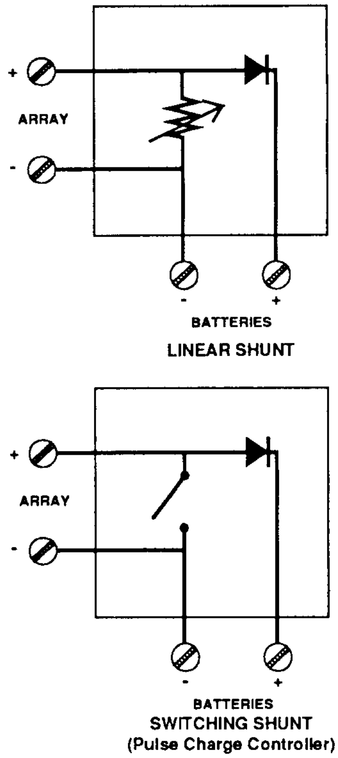
Two basic methods exist for controlling or regulating the charging of a battery from a PV module or array - series and shunt regulation. While both of these methods can be effectively used, each method may incorporate a number of variations that alter basic performance and applicability. Following are descriptions of the two basic methods and variations of these methods.

Shunt controller

A shunt controller regulates the charging of a battery by interrupting the PV current by short-circuiting the array. A blocking diode is required in series between the battery and the switching element to keep the battery from being shortened when the array is shunted. This controller typically requires a large heat sink to dissipate power. Shunt type controllers are usually designed for applications with PV currents less than 20 amps due to high-current switching limitations (Figures 2-57).

Shunt-linear: This algorithm maintains the battery at a fixed voltage by using a control element in parallel with the battery. This control element turns on when the VR setpoint is reached, shunting power away from the battery in a linear method (not on/off), maintaining a constant voltage at the battery. This relatively simple controller design utilizes a Zener power diode which is the limiting factor in cost and power ratings.

FIGURE 2-57
Block Diagram of
Linear and Switching
Shunt Charge
Controllers



Shunt-interrupting: This algorithm terminates battery charging when the VR setpoint is reached by short-circuiting the PV array. This algorithm has been referred to as "pulse charging" due to the pulsing effect when reaching the finishing charge state. This should not be confused with Pulse-Width Modulation (PWM).

Series Controller

Several variations of this type of controller exist, all of which use some type of control element in series between the array and the battery (Figures 2-58, 2-59, and 2-60).

Series-interrupting: This algorithm terminates battery charging at the VR setpoint by open-circuiting the PV array. A blocking diode may or may not be required, depending on the switching element design. Some series controllers may divert the array power to a secondary load.

Series-interrupting, 2-step, constant current: Similar to the series-interrupting however, when the VR setpoint is reached, instead of totally interrupting the array current, a limited constant current remains applied to the battery. It is expected that this will allow for an increased charging effectiveness of the basic series interrupting algorithm.

Series-interrupting, 2-step, dual setpoint: Similar to the series-interrupting, however there are two VR setpoints. A higher setpoint is only used during the initial charge each morning. The controller then regulates at a lower VR setpoint for subsequent cycles for the rest of the day. This allows a daily gassing period or equalization of the battery.

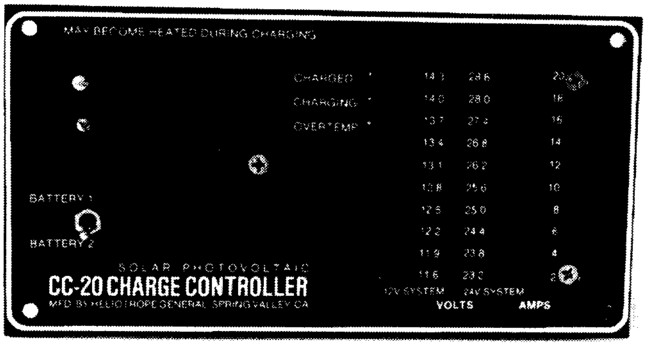


FIGURE 2-58
A Pulse-Width Modulated (Series-interrupting Solid State) Charge Controller

Photo Courtesy of Heliotrope General

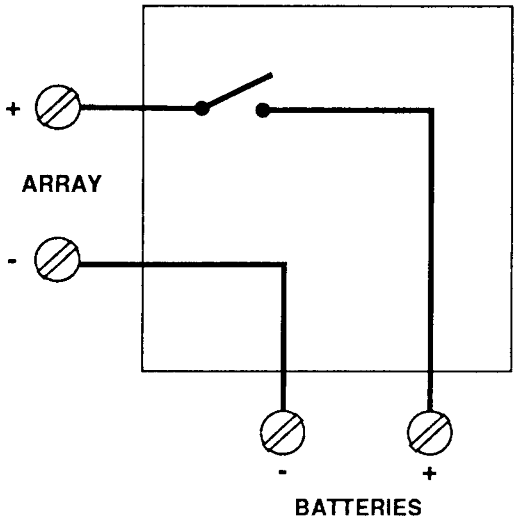


FIGURE 2-59
Block Diagram of a Series Interrupting Relay Charge Controller

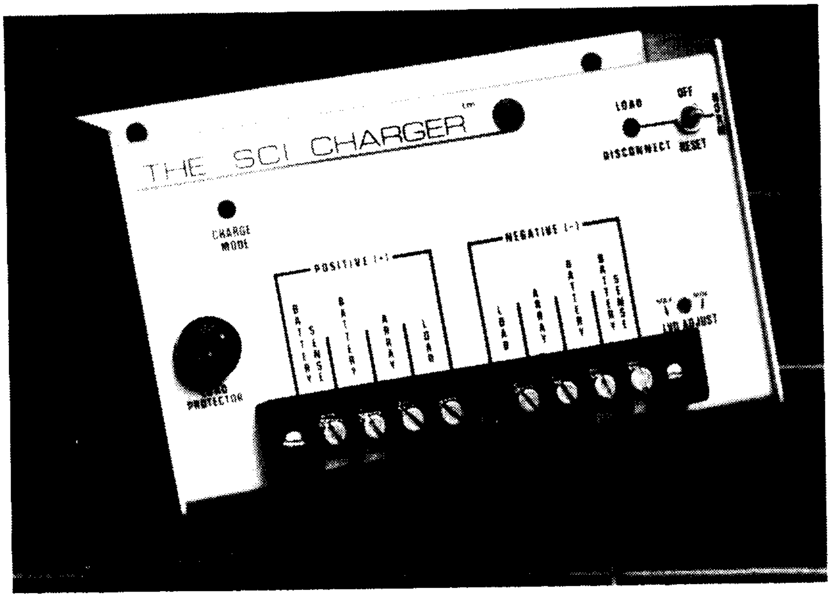


FIGURE 2-60
A Series Interrupting Relay Charge Controller

Photo Courtesy of Specialty Concepts, Inc.

Series-interrupting, Pulse-Width Modulated (PWM): This algorithm uses a series element which is switched on/off at a variable frequency with a variable duty cycle to maintain the battery at the VR setpoint. Similar to the series-linear, constant-voltage algorithm in function, power dissipation is reduced with the series-interrupting PWM algorithm.

Series-interrupting, Sub-Array Switching: Typically used in systems with more than 6 PV modules or current greater than 20 Amperes. The array is sub-divided into sections, switched individually (3-5 sub-arays). As the battery becomes charged the sub-arrays are switched off in a sequence of voltage steps to reduce current and maintain battery voltage and not overcharge the system.

This minimizes the need for high current switching gear and reduces problems associated with high current and voltage drops in the sytem. Moldularity provides simple maintenance. As a by-product, when sub-arrays are switched off charging the power can be used for a secondary non-critical load.

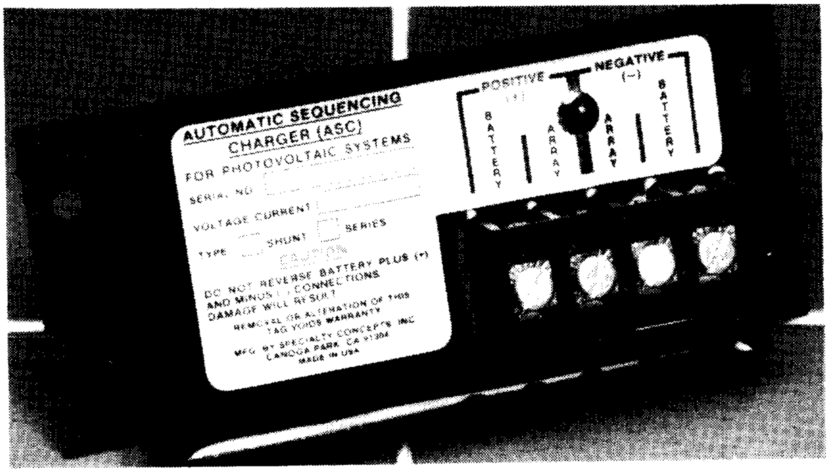


FIGURE 2-61
A Shunt-Interrupting Pulse Charge Controller

Photo Courtesy of Specialty Concepts, Inc.

Series-linear, constant-voltage: This algorithm maintains the battery voltage at the regulation setpoint (VR). The series control element acts like a variable resistor to maintain the battery at the VR setpoint. The current is controlled by the series element and the voltage drop across it. This is the recommended charge algorithm for sealed, valve-regulated batteries.

Over discharging protection

Some charge controllers also prevent the battery from discharging too deeply. If the loads which are served by the battery can be disconnected to protect the battery, they are wired through the charge controller. This feature is called "low voltage disconnect," abbreviated "LVD."

Instead of disconnecting the loads, some charge controllers use a beeper or light to alert the system user of low voltage in the batteries. The user then disconnects or turns off the loads until the batteries can recharge.

Other charge controllers turn on some type of auxiliary energy supply to recharge the batteries or power the loads. A generator is usually used for this purpose.

Temperature Compensation

The charging characteristics of batteries change with their temperature. Some charge controllers feature a temperature probe to determine the batteries' temperature, and circuitry to adjust the voltage settings accordingly (Figure 2-62).

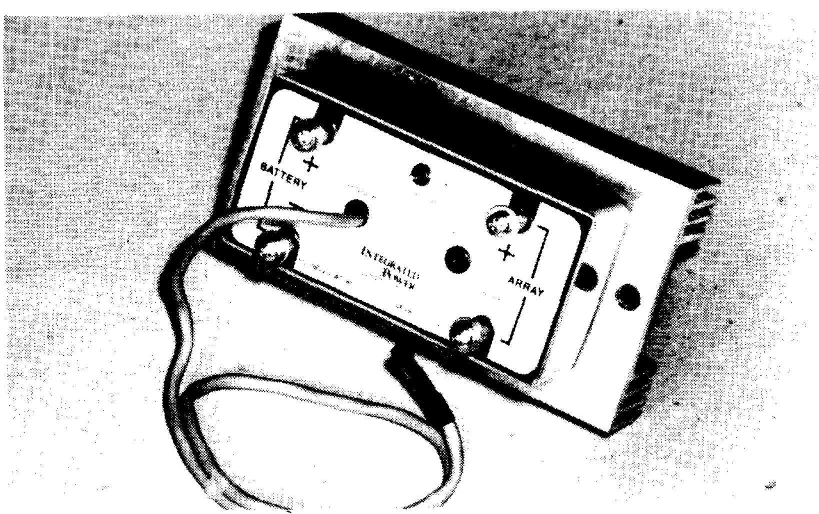


FIGURE 2-62
Charge Controller
with Temperature
Probe

Photo Courtesy of Integrated Power Corp.

The temperature probe must be in good thermal contact with the side of one of the batteries in the center of the battery bank. It must never be immersed in the electrolyte of a battery or attached to a battery terminal!

Temperature compensation of the VR setpoint is often incorporated in controller design, and is particularly desirable if battery temperature ranges exceed $\pm$ 5°C at ambient temperatures (25°C). For flooded lead-acid batteries, a widely accepted temperature compensation coefficient is -5mv/°C/cell (Reference 3). If the electrolyte concentration has been adjusted for local ambient temperature (increase in specific gravity for cold environments, decrease in specific gravity for warm environments) and temperature variation of the batteries is minimal, compensation may not be as critical.

Load Controls

Some charge controllers have a relay or solid state load control built into the controller, generally referred to as an "LVD." These can be used to turn the load on or off, turn on a generator to recharge the batteries, or signal the user that there is a low battery.

Some LVD's are built to specifically control lighting. Most sense array current to determine when to turn on a light along with a timer to determine how long to leave the light on. This method has proven to be more reliable than using a photocell to turn the light on.

When using a solid state LVD, care should be taken to not exceed the current rating of the switch, as this will destroy the unit. An example would be the high starting current of a low pressure sodium vapor lamp or a motor. Some LVD's incorporate a 5 - 10 second timer so they do not disconnect a load due to the temporary reduction of battery voltage when switching a load with high surge currents.

Array power diverter

Some charge controllers have the ability to divert power from the photovoltaic array to a non-critical load when the batteries are fully charged. The load can be a water pump for irrigation, an electric heating element in a water heater, or others.

Since this excess energy would have been lost otherwise, the size or efficiency of the load is not a primary concern. In fact, the more it uses photovoltaic electricity, the better. If there is no way to completely satisfy the non-critical load, every bit of photovoltaic electricity generated by the modules will be used.

Readouts and Light Emitting Diodes (LEDs)

Many charge controllers include an LED which is lit when the batteries are fully charged (Figure 2-62). Some have another LED to show when the photovoltaic array is charging the batteries. Another LED can show when the batteries' state of charge is too low.

A voltmeter is sometimes used to display the voltage at the batteries (Figure 2-60). This meter acts as a sort of "gas gauge" for the system, showing the batteries' approximate state of charge.

Amphour meters measure the number of amphours removed or input to the battery. This type of meter is very helpful in determining the amount of capacity removed from a battery. These may display an accurate accounting of the amphours input to the battery, but not a true accounting of the amphours stored in the battery. This is primarily due to the effectiveness of the charging algorithm.

An ammeter can tell the user the current flow out of the batteries. It functions as a "speedometer," describing how rapidly energy is being used by the loads. Another use for an ammeter is to show the current flow from the array into the batteries. This time, it shows the flow of energy being stored for future use (Figure 2-63).

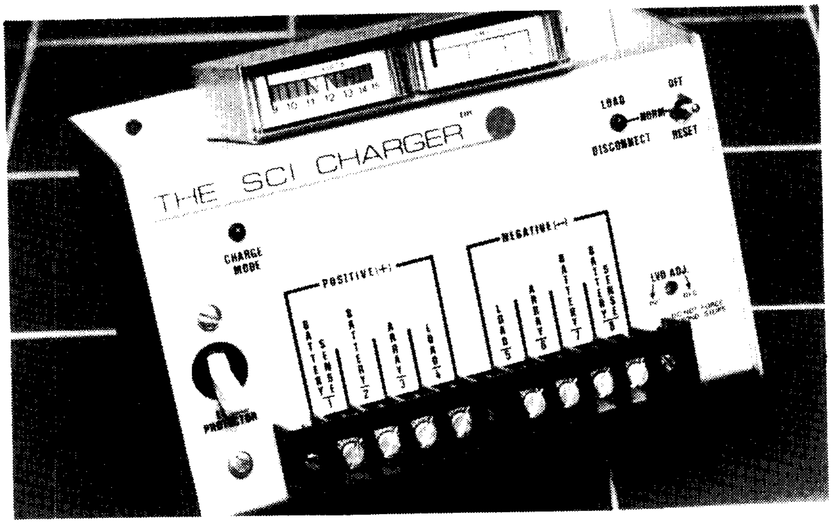


FIGURE 2-63
Charge Controller with Charging Indicator LED, Voltmeter, and Ammeter

Photo Courtesy of Specialty Concepts, Inc.

Another monitoring device is a meter showing the amount of insolation (incident solar radiation) striking the array. By measuring how much energy is available, the user can estimate system performance.

Readouts and LEDs describing system performance make troubleshooting and maintenance operations easier. At the very least, a photovoltaic system should include a meter showing battery voltage. Readouts should be on only when a reading is being done. Since LEDs also provide warnings, these may be on continuously.

Environmental requirements

As previously discussed, linear type charge controllers require adequate ventilation to allow the heat they generate to dissipate.

All charge controllers are sensitive electronic devices that must be protected from corrosion. They must be used in a clean, dry, reasonably cool environment. They must not be installed inside the battery enclosure. They are sensitive to RFI and EMI, so they must be isolated from sources of electronic "noise." Inexpensive inverters are a common source of noise in photovoltaic systems.

Although this is not under the heading of environmental conditions, the use of properly sized wire and appropriate terminal connectors will help total system performance, including that of the charge controller.

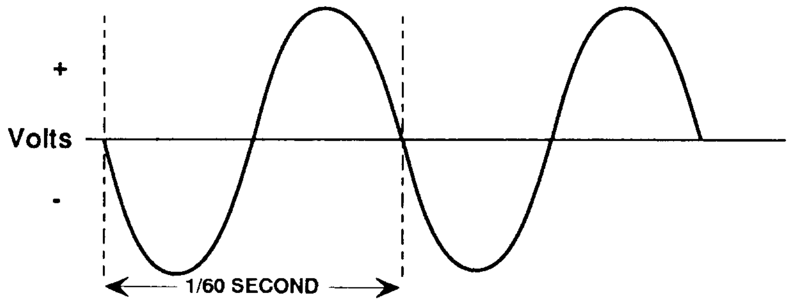
Appendix E lists the characteristics of various types and models of charge controllers available as of December 1991. The specifications of specific units will change, so the manufacturer's literature, if available, should be used instead of this list.

2.5.3 Inverters. Although the most efficient system is one using nothing but DC loads, there are times when an AC load must be supplied with photovoltaic electricity. The use of an inverter makes this possible.

Inverters convert DC into AC. DC has a current flow in only one direction, while AC rapidly switches the direction of current flow back and forth.

Typical AC in the United States is 60 cycles per second (60 Hz). Each cycle includes the movement of current first one way, then the other. This means the direction of current flow actually changes 120 times per second (Figure 2-64).

FIGURE 2-64
Alternating Current
Flow and Waveform



The AC delivered by a utility company or a diesel or gasoline generator is like that shown in Figure 2-64. The changes in current flow direction are gradual, so a graph of the voltage through the cycles is a "sine" wave. Sometimes it is referred to as "sinusoidal."

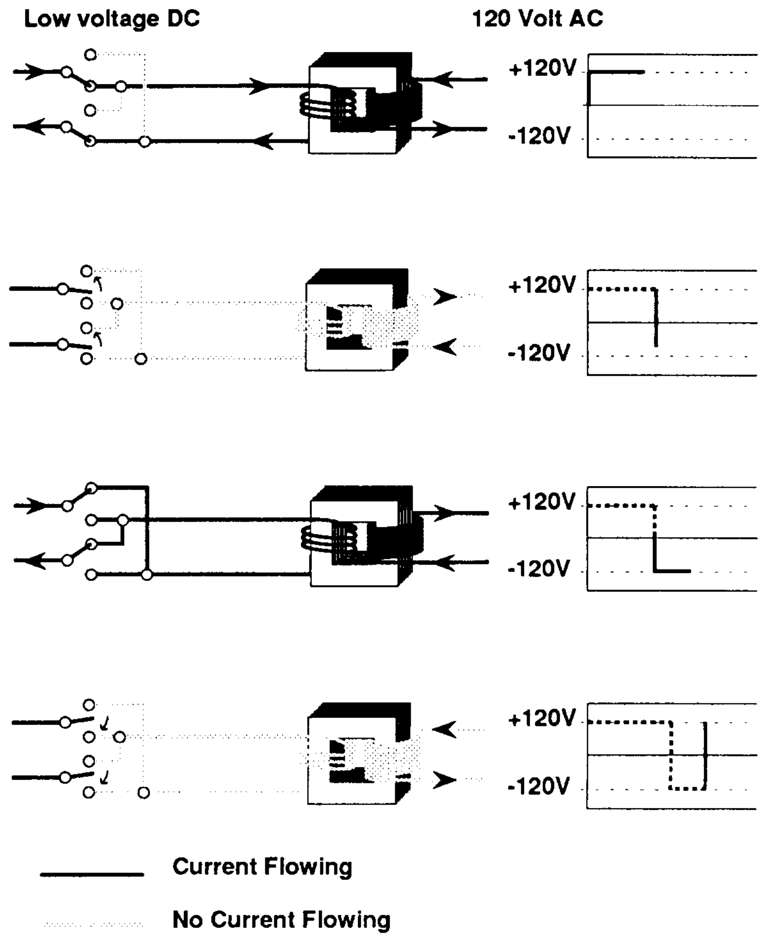
Converting DC to AC can be done a number of ways. The "best" way depends on how close to the ideal sine wave the AC has to be for satisfactory operation of the AC load.

All inverters require the same clean, dry, and reasonably cool environment as charge controllers or any other electronic devices. They should be located reasonably close to the battery bank, but not inside the battery enclosure.

Square wave inverters

Most inverters operate by sending the direct current through a step-up transformer first in one direction, then in the other (Figure 2-65). The switching device which changes the direction of the current must operate

FIGURE 2-65
Basic Inverter
Operation



very rapidly. Solid state devices such as power transistors or silicon controlled rectifiers (SCRs) are used to perform this function.

As current moves through the primary side of the transformer, the polarity is reversed 120 times each second. As a result, the current emerging from the secondary side is alternating, going through 60 complete cycles per second. The simplest inverters do little else beyond this operation. As a consequence, the AC output is also very simple. The direction of current flow through the primary side of the transformer is changed very abruptly, so the waveform of the secondary side is "square" (Figure 2-66). Square wave inverters are the least expensive, but they are typically the least efficient as well.

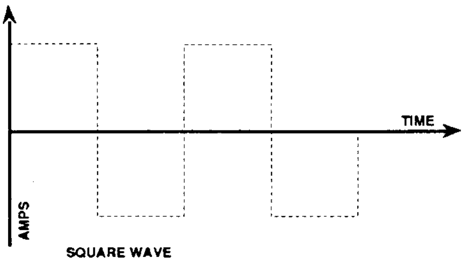


FIGURE 2-66
Square Waveform

Modified or quasi-sine wave inverters

More sophisticated and expensive inverters use fixed pulse width modulation techniques. The waveform is modified after the transformer to bring it closer to a sine wave.

The output is still not a true sine wave, but it is closer (Figure 2-67). These waveforms, and the inverters that produce them are called "modified sine wave" or "quasi-sine wave" (Figure 2-69).

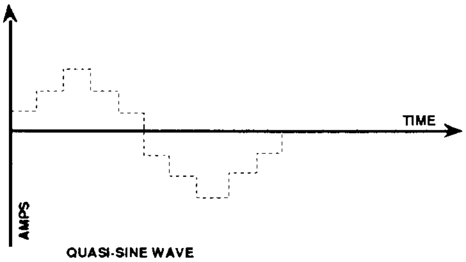


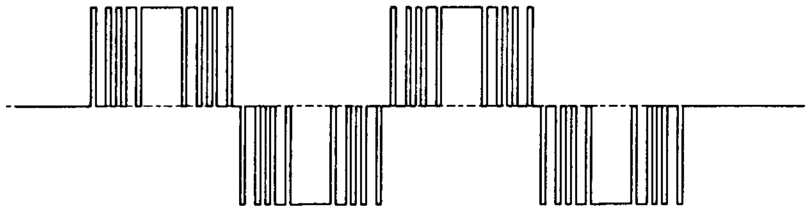
FIGURE 2-67
Modified or Quasi-Sine Waveform

Modulated pulse-width waveform inverters

Another way to approximate a sine wave uses high switching speeds. Both directions of DC input to the transformer are turned on and off rapidly in a particular pattern. The resulting waveform looks like a picket fence.

The width of the "on" pickets is narrow during those times when the height of a sine wave is low. As the picket fence gets closer to the peak of a sine wave, the pickets get wider and wider (Figure 2-68). Output filtering is used to reconstruct the sinusoidal wave shape.

FIGURE 2-68
Modulated Pulse-Width Waveform



The same pattern is repeated, in a negative direction, through the second half of the cycle. The end result is actually only a complex square wave, but it is perceived by loads as closely equivalent to a sine wave. Switching of this type is normally done by field effect transistors (FETs).

<u>Sine wave inverters</u>

With an oscillator and an amplifier, true sine waveform AC can be produced. However, these inverters are large and expensive. They can be very inefficient, sometimes operating at only 30-40% efficiency.

Newer solid state sine wave inverters have been developed which operate at efficiencies of 90% or better depending on the size of the load. These are more reasonably priced, but are still above the costs of less sophisticated inverters.

Another method is to use a DC motor to turn an AC generator. The efficiency of this method is also low, but it may be appropriate for critical AC applications. These inverters typically have a fairly small capacity.

Because only the most sophisticated AC loads require pure sine waveform power, the least expensive and most efficient inverter that will operate the load should be used.

<u>Synchronous inverters</u>

Photovoltaic systems connected to the utility grid can use synchronous inverters. These are sometimes called "line-commutated." These inverters use the waveform from the utility AC line as a pattern to convert photovoltaic DC into AC.

Since this manual is devoted exclusively to stand-alone photovoltaic systems, these grid-connected systems will not be covered further.

Inverter capacity

Inverters are sized in two ways. The first is the number of watts of electrical power the inverter can supply during normal operation for typical periods of time.

As shown in Figure 2-70, inverters are less efficient when they are using a small percentage of their capacity. For this reason, they should not be oversized. They should be matched fairly closely to the load.

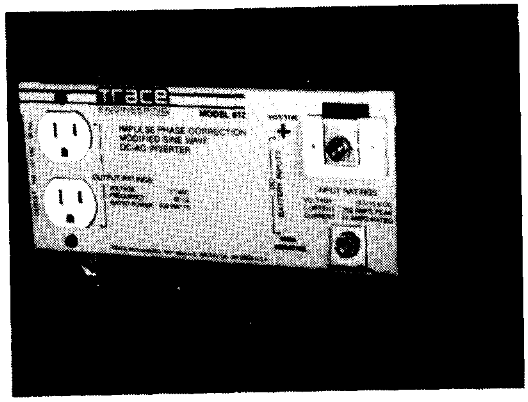
The second inverter capacity measurement is surge capacity. Some inverters can handle more than their rated capacity for short periods of time. This ability is important when starting motors and other loads which require from two to seven times as much power to start up as they do to run once they are started (Table 2-6).

Inverters are available for different nominal input voltages, and must be chosen accordingly.

TABLE 2-5: Characteristics of Typical Inverters

	Square Wave	Modified Sine Wave	Pulse-Width Modulated	Solid State Sine Wave
Standard Output (watts)	Up to 1,000,000	300 to 2,500	Up to 20,000	Up to 2,000
Surge Capacity (watts)	Up to 20 times standard output	Up to 4 times standard output	Up to 2.5 times standard output	Up to 4 times standard output
Typical efficiency over entire output range	70% to 98%	70% to 85%	-90%	Up to 80%
Harmonic Distortion*	Up to 40%	Around 5%	Less than 5%	Almost None

* Harmonic distortion should be as low as possible. It describes errors in the total wave form caused by the component waves which make it up.



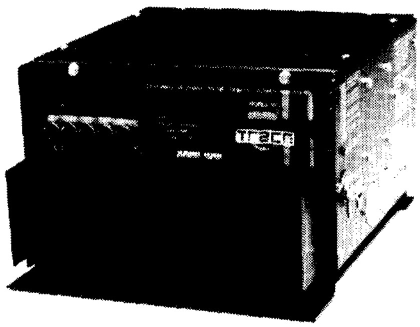
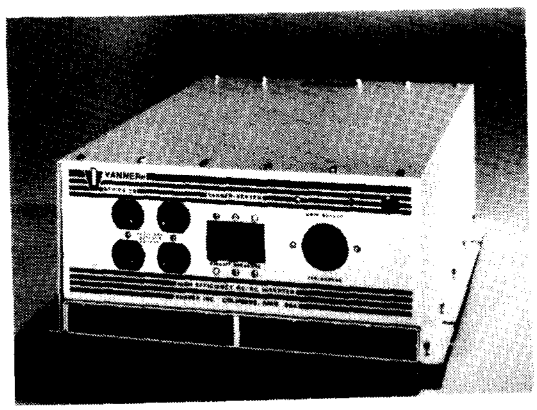
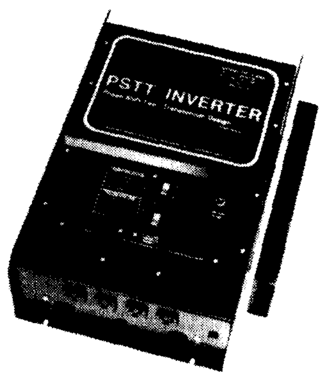


FIGURE 2-69
Modified Sine Wave
Inverters

Photo Courtesy of
Trace Engineering Co. (top and second)
Vanner, Inc. (third)
Heliotrope General (bottom)





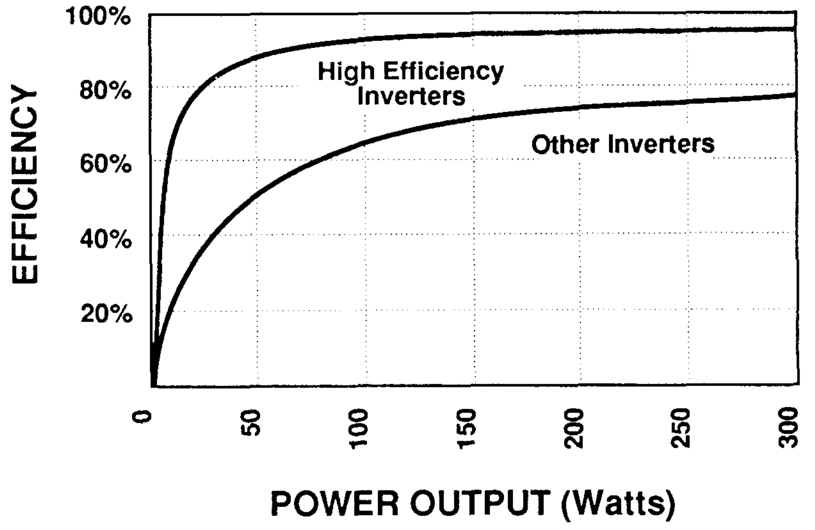


FIGURE 2-70
Typical Inverter
Efficiency Graphs

Effect of load on efficiency

An inverter always uses power when it is running, even if no loads are connected and drawing power. This "idling" or "no-load" loss is why the efficiency of the inverter is zero in a no-load situation.

As the size of the load increases, the inverter efficiency increases. The efficiency of a typical inverter is quite low until it is supplying at least 10% of its rated capacity (Figure 2-70).

Because inverter efficiency is zero when it is "idling," older inverters check to see if a load is on every few seconds. As long as there is no load requiring power, the inverter stays off, or nearly off. This feature is called load demand start or automatic load demand. When a load is sensed, the inverter comes on. This is why there is a momentary delay in starting up AC appliances with older inverters equipped with this feature. Newer designs have no noticeable delay.

Inverter options

A variety of options are available for most inverters. These include:

Load demand start. Previously described, this feature keeps the inverter from idling and wasting power unless there is a load to be served.

Battery charger. This allows the inverter to also be used as a battery charger, if the system includes a motor-driven generator making AC power.

Meters and LEDs. Just as these devices help the user of a charge controller, they help the inverter user with normal operation and troubleshooting. Some inverters can be equipped with a remote monitor for convenience.

Remote control. Since many inverters are turned off when the loads are not being used, a remote control switch can be a convenient addition.

Low voltage disconnect. If voltage from the batteries gets too low, some inverters will shut off until the voltage rises back up. Like a charge controller's low voltage disconnect, this protects the batteries from discharging too deeply. It also protects the loads from operating at too low a voltage.

Fuses or circuit breakers. These protect the circuitry of the inverter from excessive current flows.

Reverse polarity protection. This feature protects the inverter against the accidental reversal of the DC input wiring.

Voltage window

Like batteries and charge controllers, different brands of inverters have different input voltage windows. If the input voltage is too low, the output voltage will also be too low, causing improper load operation and potential damage to the loads. The inverter should be matched with the loads and batteries for the best performance and reliability. The charge controller settings must be carefully set.

The wider the inverter input voltage window, the better, since the voltage of a photovoltaic system varies considerably. The voltage is largely determined by the battery bank voltage, for systems with batteries. Amorphous silicon modules are particularly prone to output voltage variations.

2.5.4 DC to DC Converters. If the loads require DC electricity, but at a different voltage than the system can provide, a DC to DC converter is used.

Another reason to use a converter is to increase the voltage, and thus reduce the current flow for the same amount of power delivered to the loads. This allows smaller gauge wiring to be used. The capacity of fuses or circuit breakers can also be reduced.

Like a transformer, a converter can increase or decrease the voltage; however, it is much more efficient. Converters are solid state devices technically similar to a switching power supply. Typical converters with capacities of 6 to 40 amps operate at 75-85% efficiency. Smaller capacity units operate at around 50% efficiency.

2.5.5 Power Point Trackers. In direct DC systems, with DC motors and no battery bank, or those with an inverter or DC to DC converter and a battery bank, it is practical to add a device called a "maximum power point tracker." Examples of these may be found in Appendix E, pages E-13 and E-35.

These electronic devices determine where the array is on the modules' current-voltage curve. Then it adjusts the system voltage and current to bring the array as close as possible to the maximum power point.

This helps reduce the problem of a stalled motor burning up during the morning start-up of a motor connected directly to the array.

2.5.6 Independent Monitoring Systems. Meters and LEDs reporting on the status of various system components and functions can prevent damage to the system components. They also allow the user to make more effective use of the available photovoltaic electricity (Figure 2-71).

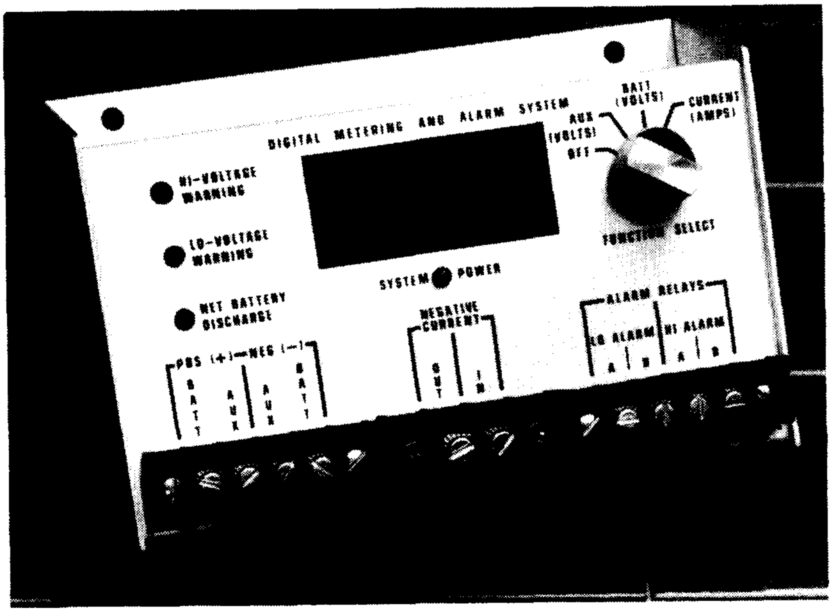


FIGURE 2-71
An Independent
Monitoring System

Photo Courtesy of Specialty Concepts, Inc.

Output relays can be used to turn on auxiliary generators, turn off non-critical loads, or perform other necessary functions. The more remote the system is, the more important it is that the system take care of itself. Output relays can operate many of the functions that make the system more independent.

The following list has the most desirable monitoring features listed first.

Battery voltage meter. This should be on every system using batteries, to display the voltage of the battery bank.

Array output current. Every system should also be able to report the amount of current flowing from the array to the load or batteries.

Charging LED. This tells the user that current is flowing into the batteries from the array, but not how much.

Fully charged LED. This LED lights when the batteries are fully charged. A meter telling the exact voltage is more desirable, but this LED at least tells the user if the array has successfully charged the batteries.

Low voltage disconnect LED. If the system has a low voltage disconnect feature, this LED lights to let the user know the loads are disconnected.

Low voltage LED or buzzer. If a system does not have a low voltage disconnect feature in the charge controller or the inverter, some type of warning is necessary to keep the batteries from being damaged. This only works if someone is there to hear or see the warning.

Load current meter. This meter tells how rapidly the loads are using power.

Polarity reversed LED. This LED tells the user the polarity of the photovoltaic electricity from the array is reversed.

Solar energy meter. In some cases, knowing the amount of available solar energy is desirable. This is especially true during inspection or troubleshooting operations.

Array or air temperature meter. On large systems, knowing the temperature of the array, or the air around it, may help explain variations in output voltage.

2.5.7 Wiring and Grounding. The correct type and wire size, appropriate wire protection, and adequate and correct grounding are critical in photovoltaic applications.

Wire sizing and ampacity tables are in Appendix C. Follow these tables carefully. Undersized wiring will cause unacceptable voltage drops. This will result in a loss of available power, and may cause some loads to work poorly or not at all. The NEC requires #12 AWG or larger conductors be used with systems under 50 volts.

DC electricity has a polarity which must be maintained throughout the system. The color conventions of wire insulation must also be maintained.

In most existing photovoltaic systems, the positive is red, the negative is black, and the equipment grounding conductor is green or bare. This is identical to the DC wire color conventions in automobiles. In power wiring systems, the NEC requires the grounded conductor to be marked white; the equipment grounding conductor bare, green, or green with a yellow strip; by convention, the first ungrounded conductor is colored black and the second red.

WARNING!

In some photovoltaic systems, the color conventions may be different. Be sure you know which color convention is being used before working on a system. Never assume the black is negative and always make sure the circuit is disconnected. Remember that high current flows, even at low voltages, can be lethal!

System component interconnections

Poor electrical connections result in losses in system efficiency, system failure, and costly troubleshooting and repairs. All system connections must be secure. They must withstand extremes of weather and temperature. They must be protected from vibration, animal damage, and corrosion.

Generally, connections are made using conventional methods. The large DC current flows of photovoltaic systems require large wire gauges. This means large connectors such as split bolt or other types of pressure connectors are used more often than in 120 volt AC systems.

Crimped connectors and soldering are used for wire to wire connections. Crimped connections should be done carefully, as a poor connection will create a significant voltage drop. Twist-on wire connectors (wire nuts) are not reliable when used on low voltage (12 - 50 volts), high current PV systems because of thermal stress and oxidation of the contacts.

Because so many photovoltaic system connections are outside, moisture and corrosion problems are more frequent. Generally, only copper conductors are used.

MAINTENANCE AND OPERATION OF STAND-ALONE PHOTOVOLTAIC SYSTEMS

A publication of the

PHOTOVOLTAIC SYSTEMS ASSISTANCE CENTER

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Revised report prepared for:	U.S. Army Construction Engineering Research Laboratory Champaign, Illinois 61820-1305
Prepared by:	Architectural Energy Corporation 2540 Frontier Avenue, Suite 201 Boulder, Colorado, 80301 (303) 444-4149

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Aluminum is not recommended, but if it is used, some method of waterproofing the junction of copper and aluminum wires must be used, as well as an appropriate connector rated for both copper and aluminum, and an anti-oxidation coating. Aluminum wire should only be used outside, never in a building.

Depending on local code requirements, environmental conditions (including gnawing damage from animals), and system design, conduit may be required. Plastic or metal in rigid or flexible styles can be used. Conventional connectors and couplings are used.

Connection and disconnection sequences

It is very important to follow the correct connection and disconnection sequences with system components. This is particularly true with batteries, charge controllers, and inverters. Failure to follow the manufacturer's sequence can destroy components or create a personal hazard.

Switches, fuses, and circuit breakers

Due to the high current flows and polarity of photovoltaic electricity, standard AC switches cannot be used. Arcing between switch contacts will quickly degrade switch performance and can cause fires.

Use switches specifically made and rated for DC electricity.

Disconnect switches, or safety switches with fuses, should be used on the array and the battery bank. These are both sources of power, and the National Electrical Code requires a disconnection method for them.

Fuses and circuit breakers are as important in a photovoltaic system as they are in any other electrical system. Circuit breakers must be rated for DC applications. The contacts of many AC circuit breakers will fail as a result of the arcing associated with interrupting a DC circuit. Use UL listed breakers such as Square D's "QO" type.

If DC circuit breakers are not available, use fuses instead. Time delay or "slow blow" fuses can be used to accommodate the current surges of starting motors, but the fuses must be UL listed or recognized for DC with DC ratings.

As with AC systems, fuses, circuit breakers, and switches in photovoltaic systems must not be in the grounded conductors. Always put a fuse or switch on the ungrounded conductor. In some bipolar systems, where the center tap is grounded, fuses and disconnects are required in both positive and negative conductors.

Grounding

Because of the polarity of DC electricity, complete and correct grounding procedures must be followed. Local, state, and national codes must be observed (Figures 2-72 and 2-73).

All junction boxes, electrical component enclosures, metal conduit and connectors, and photovoltaic module frames must be connected to an earth grounding system. This is referred to as equipment grounding.

The connection to the earth is via a grounding electrode (a rod) driven into the ground. The grounding wiring, green or bare, is securely clamped to the grounding rod. If a system ground is used, the system grounded conductor must also be connected to this rod.

If allowed by local and state code, metal conduit can function as the equipment grounding system between junction and other electrical boxes, but special fittings must be used to insure grounding continuity. If plastic conduit is used, a grounding wire must be run.

A "two-wire" DC system will have a positive conductor, a negative conductor, and a bare or green conductor. If the system is grounded (one of the current carrying conductors), then that conductor should be colored white. Systems over 50 volts must have one conductor grounded. There are no color codes in the NEC other than white for the grounded conductor and bare or green for the equipment grounding conductor.

A "three-wire" DC system has 4 wires - a grounding conductor (green or bare), a positive, a negative, and a neutral. The neutral, or center, tap must be grounded and therefore must be marked white. Other colors are optional for positive and negative (usually red and black, respectively).

In some systems, the positive conductor may be grounded. Telephone systems are an example. Any system over 50 volts (open circuit array voltage) must have one of the current carrying conductors grounded. For maximum safety and minimum radio frequency interference from inverters and fluorescent lamps, it is suggested that all systems have one conductor grounded (usually the negative).

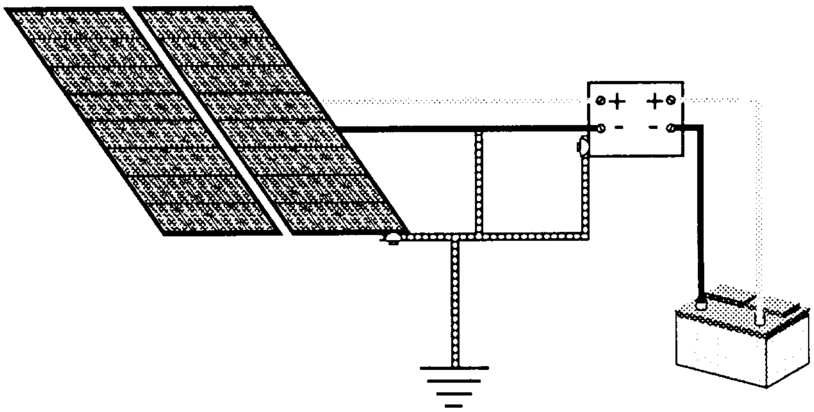


FIGURE 2-72
Grounded System
(negative conductor)
with Equipment
Grounding Conductor

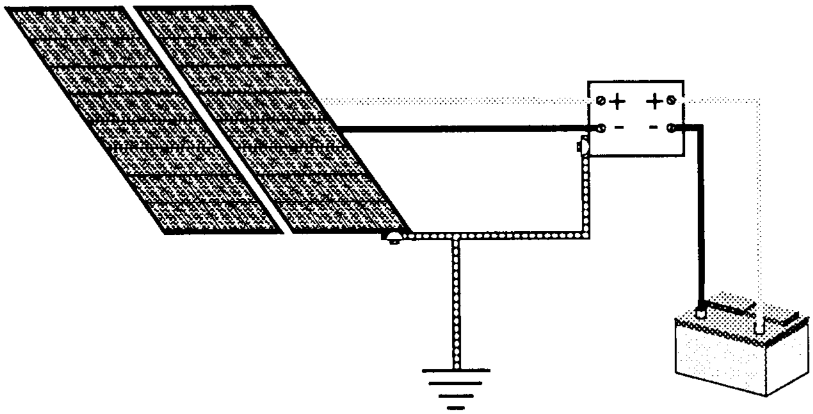


FIGURE 2-73
Ungrounded System
with Equipment
Grounding Conductor

2.6 QUESTIONS FOR SELF-STUDY

Directions: Choose the best answer to each question.

1) The electricity produced by photovoltaic cells is:

A) Alternating current
B) Direct current
C) Three-phase
D) Static

2) Which of the following is a major factor in the operation and maintenance of photovoltaic systems?

A) Voltage drop
B) Equipment connection sequences
C) Equipment disconnection sequences
D) All of the above

3) Which of the following components does a self-regulating system always use?

A) Photovoltaic module
B) Inverter
C) Charge controller
D) None of the above

4) A photovoltaic cell with a uniform blue color is a:

A) Single-crystal
B) Polycrystal
C) Thin film
D) Amorphous

5) Adding cells in series to a photovoltaic module will:

A) Decrease the voltage
B) Increase the voltage
C) Decrease the current
D) Increase the current

6) The maximum power point of a module's current vs. voltage curve is:

A) At the far left of the curve
B) At the far right of the curve
C) At the highest point of the curve
D) At the knee of the curve

7) The most common photovoltaic modules have:

A) 24 cells
B) 28 cells
C) 32 cells
D) 36 cells

8) A device which allows current to flow in only one direction is a:

A) Resistor
B) Transformer
C) Diode
D) Fuse

9) Reflectors can be used

A) In any climate, clear or cloudy
B) With any type of photovoltaic module
C) With any mounting system, fixed or tracking
D) None of the above

10) A site in San Diego (latitude 32°N) has a photovoltaic system used mostly in the winter. What should the tilt angle of the modules be?

A) 17°
B) 32°
C) 47°
D) 62°

11) Which of the following will reduce the capacity of a lead acid battery?

A) Operating at 80°F
B) Rapid discharge rate
C) Extremely slow discharge rate
D) Very shallow charge-discharge cycles

12) Each cell in a lead acid battery delivers how many volts?

A) 1
B) 2
C) 3
D) 6

13) What features can charge controllers have?

A) Overcharging protection
B) Low voltage disconnect
C) Stopping reverse current flow at night
D) All of the above

14) What do inverters do?

A) Change DC voltage to a different DC voltage
B) Provide voltage pulses for battery charging
C) Convert DC to AC
D) Convert two-phase AC to three-phase AC

15) Which is the correct color convention for DC wiring in photovoltaic systems?

A) Positive is red, negative is black, ground is bare
B) Positive is black, negative is red, ground is bare
C) Positive is black, negative is red, ground is white
D) Positive is red, negative is white, ground is bare

3.0 INSPECTION

What You Will Find In This Chapter

This chapter contains information on inspection of photovoltaic systems. The material is sufficient for an Annual Control Inspection (ACI), when no repairs or maintenance operations are to be performed.

It is assumed that you are familiar with basic electrical concepts and can use electrical meters to measure current, voltage, and resistance. It is strongly suggested that you read all of Chapter 2 before undertaking any inspection. If this is not possible, at least read Section 2.1, Photovoltaic Electricity.

Tools and supplies necessary to perform inspection operations are listed in Appendix A.

An inspection checklist is at the end of this chapter.

3.1 INSPECTION PROCEDURES

3.1.1 General. The inspection procedures which follow take you step by step through a complete inspection. If you are inspecting a system which does not have a particular component, skip over that subsection. If you believe a system is missing a particular component, refer to Section 2.3, which describes the basic systems and their components.

The worksheet at the end of this chapter is in the same sequence as the text in the chapter. You may find it convenient to use it as a checklist or to remind you of each of the inspection steps.

Figure 3-1 is a schematic of a typical photovoltaic system, showing the test points referred to frequently throughout this chapter.

It may not be possible to perform a complete inspection unless it is a clear, sunny day. Even intermittent clouds cause problems. If possible, schedule inspections on a clear day.

WARNING!

Even at the low voltages typically used, photovoltaic battery banks and photovoltaic arrays both contain lethal amounts of current! Photovoltaic arrays make electricity whenever light shines on them. Modules can only be "turned off" by covering them with an opaque material, facing them to the ground, or working at night. Use insulated tools when working on electrical components.

Lead acid batteries are filled with high concentration sulfuric acid and give off explosive hydrogen gas while charging. Wear proper eye and skin protection, have baking soda and water available for emergencies, and do not smoke or use fire or spark sources near batteries.

Permission to disconnect critical loads

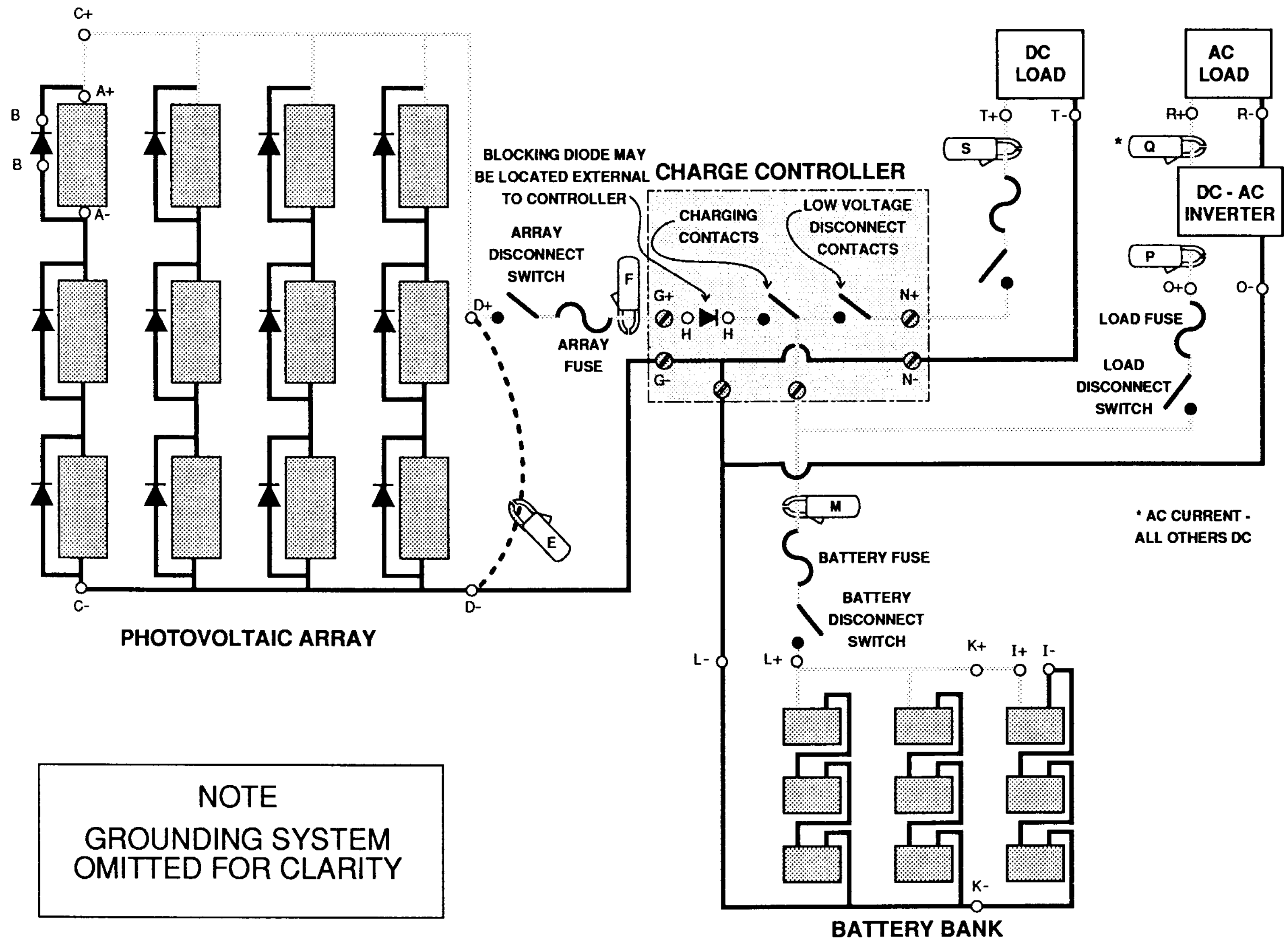
Many photovoltaic systems power critical loads, such as communication or warning lights. Be sure to get permission from the appropriate authority to disconnect such loads before doing so. In some cases, an auxiliary power supply may be necessary to operate the load while it is being inspected.

Be sure that you have all the necessary tools, materials, and supplies with you to minimize the system "down time."

3.1.2 System Meters. Leave all disconnect switches closed (turned on) at this time. If the system has meters, note their readings first. Confirm every system meter reading with portable meters as well. Do not assume that the portable meter is more accurate than system meters. If a discrepancy occurs, check the portable meter before recalibrating or replacing system meters. It is a good idea to periodically calibrate all field instruments.

Array voltage

Use a DC voltmeter to measure the voltage in the array circuit. This will let you know if the modules are producing voltage and if the array circuit is complete. Check the voltage from the positive conductor to ground, from the negative conductor to ground, and between the positive and negative conductors. Record the voltages on the inspection worksheet.



NOTE
GROUNDING SYSTEM OMITTED FOR CLARITY

FIGURE 3-1
Photovoltaic System Test Points

CAUTION!

The open circuit voltage of photovoltaic modules is almost twice as high as the module's nominal voltage. For example, a "12 volt" module's open circuit voltage is from 20 to 22 volts. If a disconnect switch is inadvertently opened or a connection is broken, the modules will be operating at their open circuit voltage. In addition, modules in series add their voltages.

If the system includes a meter showing the array voltage, make sure its reading is within 10% of the reading from the portable meter.

Battery voltage

First, check the total battery voltage, at test points L+ and L-, as shown in Figure 3-1. This roughly describes their state of charge, and indicates what mode the charge controller should be in. (Batteries will be checked in more detail later.) Use the system battery voltage meter, if one exists, and a portable DC voltmeter. Make sure the two readings are within 10% of each other. Record the voltage on the inspection worksheet.

If the battery voltage is below the voltage regulation setpoint for the controller, and the sun is out, make sure the controller is allowing current from the array to charge the batteries.

When the voltage is above the voltage regulation setpoint, no charging should take place. This is true even if the sun is out.

If the controller has a pulse or trickle charge feature, it should be supplying a pulsing or small float current when the voltage is between the charge resumption and termination thresholds. The pulses may be minutes apart as the battery voltage gets very close to the termination setting.

Array output current

This test must be done when there is a reasonable amount of sun. There may be an LED indicating "charging" on the charge controller. The charge controller or stand-alone metering may have an ammeter to indicate current flow from the array. If so, note the current reading on the inspection worksheet.

Whether or not these are in the system, use a DC snap around (clamp-on) ammeter to determine the array output current. To do this, disconnect the array from the system, short the array with an appropriate gauge wire (see Appendix C) connected from points D+ to D-. Compare this reading to any system array current meter reading that was previously noted. Record the results on the inspection worksheet and then remove the test short connection and reconnect array.

> CAUTION!
>
> The current from the array may be very high. Make sure the meter has a high enough range to prevent "pegging" it. Also make sure that the meter is suitable for measuring DC current. The most common type of snap-around (clamp-on) current meters can only be used to measure AC current and may be damaged if used on DC current.

If the battery voltage is below the charge resumption threshold for the controller, and the sun is out, make sure the controller is allowing electricity from the array to charge the batteries.

When the voltage is above the charging termination threshold, no charging should take place. This is true even if the sun is out.

If the voltage is below the charging resumption threshold, and the sun is out, the controller should be allowing the array to charge the batteries.

If the controller has a pulse or trickle charge feature, it should be supplying a pulsing or small float current when the voltage is between the charge resumption and termination thresholds. The pulses may be minutes apart as the battery voltage gets very close to the termination setting.

Other Indicators and Meters

While the system is still operating, check any other status indicators and meters in the system. Again, check system meters' accuracy against portable meters. Make sure that the indicators are correct.

Check LED status lights on the charge controller, if any. Make sure they are reporting the actual condition. If the battery voltage is low, the "charging" LED should be on; if the battery voltage indicates a full state of charge, an LED indicating "fully charged" should be on.

3.1.3 Portable Metering. At this time, open (turn off) all disconnect switches. Recheck the overall battery voltage. Use an ohmmeter to check the continuity of the entire grounding system. Make sure that all module frames, metal conduit and connectors, junction boxes, and electrical components chassis are earth grounded.

Using a DC voltmeter, check the polarity of all system components and wiring. Although some system components and loads operate satisfactorily with reversed polarity, service personnel and most equipment are at risk when polarities are reversed.

If plastic conduit is used, make sure a grounding wire has been run through it to provide continuous grounding. If metal conduit is used, the conduit itself functions as the ground conductor, where allowed by code. If not allowed by code, a grounding wire must be used.

Make sure the earth ground rod is driven far enough into the ground (8 foot minimum). An adequately driven rod cannot be pulled up or easily pushed sideways by hand. Confirm that a clamp was used to connect the ground wire and rod together.

Normally, the negative conductor should be tied to the earth ground. Section 2.5.7 in the previous chapter contains more information on grounding.

3.1.4 Disconnect Switches and Fuses. At a minimum, there should be a disconnect for the array and the battery bank. If there is not, note this on the inspection worksheet. Every source of voltage must have some means of disconnection.

WARNING!

If the battery bank does not have a disconnect switch, be very careful when removing a wire from right at the batteries. If the batteries are charging, and the hydrogen gas being given off has not been properly vented, it can be ignited by the spark, resulting in an explosion. Make sure the battery enclosure is properly vented.

> CAUTION!
>
> If it is necessary to disconnect wires instead of turning off switches, be sure to follow the correct disconnection sequence for the charge controller. Disconnecting or reconnecting in the wrong sequence can damage some controllers. Section 2.5.2 has information on specific controllers, but refer to the manufacturer's information for the specific control in the system, if it is available.

3.1.5 System Wiring. Use a DC voltmeter to confirm that the wiring and components turned off by the disconnect switches are disconnected. Check between the positive and the negative conductors, the positive and ground conductors, and the negative and ground conductors. If any wiring is live which is not supposed to be, note it on the inspection worksheet, and find a way to disconnect it.

Check all wire insulation for the correct color convention. In DC photovoltaic systems, the ungrounded conductor(s) should be black or red, the grounded conductor white, and the equipment grounding conductor should be green or bare. The hot AC line should be black, the neutral or common should be white, and the equipment grounding conductor should be green or bare.

Check all switches, circuit breakers, and relay contacts for evidence of arcing. If any is found, note it on the inspection worksheet, along with the nameplate amp rating of the damaged device. Undersized components will have to be replaced.

Visually check all conduit and wire insulation for damage. Inappropriate wire insulation may degrade in sunlight, moisture, or in the ground. Both conduit and wire insulations may suffer from animal damage.

Remove junction box and component covers. Check for loose, broken, corroded, or burnt wiring connections. Make a note on the inspection worksheet of any damage you find. Replace all covers.

3.1.6 Charge Controllers. Check to make sure the power is off at the charge controller. If it is necessary to disconnect live wires, be sure to follow the correct disconnection sequence for the charge controller. Follow the manufacturer's instructions, if available, for the specific charge controller in the system.

Connections and wires

Check all terminals and wires for loose, broken, corroded, or burnt connections or components. Make sure there are no loose strands of multistrand wire. These can short out on other terminals or other wires' loose strands.

Temperature compensation probe

Check the terminal connections of the temperature compensation probe, if the charge controller is equipped with one. Be sure the probe is in good thermal contact with the side of one or more batteries. The probe must not be immersed in electrolyte. The acid will destroy it.

The charge controller manufacturer may be able to supply a chart showing the resistance or voltage through the sensor in the temperature compensation probe. If this is available, check the sensor for proper calibration.

Environmental conditions

The charge controller should be clean. It should be securely mounted in a dry, protected area. It should not be subjected to unreasonable temperature extremes. Most controllers are able to withstand a temperature range of 32-100°F. Beyond this range their calibration will drift and they may be damaged.

Make sure the charge controller is not installed in an unventilated space with the batteries. The hydrogen gas generated by charging can be ignited by sparks from the controller relay, even during normal operation.

Optional operation test for shunt charge controllers

SCI shunt type charge controllers, described in Section 2.5, can be tested by disconnecting one battery terminal connection from the controller. Put a wire nut on the exposed bare wire.

Use a DC voltmeter to measure the voltage between the array positive (D+) and array negative (D-) terminals. If there is a reasonable amount of sun, it should be 18 to 20 volts per module in series. This will vary with the type of module and the length and size of wiring between the array and the charge controller.

Now measure the DC voltage between the battery (L+) positive and battery negative (L-) terminals on the controller. If the controller is operating properly, it should be between 13.5 and 14.5 volts per module in series.

Reconnect the battery wire to the controller's battery terminal.

Optional operation test for series-interrupting relay charge controllers

If a portable adjustable power supply is available, use it to perform the following operation test.

The steps in this test assume a simple, single stage series-interrupting relay charge controller, as described in Section 2.5. The only added features this controller has are indicator LED's and low voltage disconnect.

If the controller has a temperature compensation probe, remember that the charge termination and resumption settings will vary with temperature.

Tests for other features are described after the basic testing steps.

Required materials are:

- 0-20 volt DC portable adjustable power supply
  (for 12 volt controllers, higher for other ratings)
- DC voltmeter
- Ohmmeter
- Manufacturer's specifications for the charge controller
- Ammeter (only if testing a multi-stage controller)

NOTE

The power supply listed above is the right one for a 12 volt charge controller. The example voltages in the figures and text are appropriate for 12 volt systems. Controllers in higher voltage systems will require power supplies with correspondingly higher voltage outputs.

Step 1: Following the manufacturer's recommended sequence, disconnect all wiring from the controller, except the temperature compensation probe, if the controller has one. Set the power supply to zero volts.

Step 2: Connect the power supply and DC voltmeter to the controller's + and - "array" input terminals. Be sure to observe the correct polarity. Do not reconnect any other wires. Current limit the supply by setting current limit on supply or adding a series resistor in positive leg to limit to safe current for controller.

Step 3: Watching the meter, slowly increase the power supply voltage until it is equal to the nominal voltage rating of the charge controller.

At some point during this step, the controller should start trying to charge the batteries, and the "charging" LED will come on. This is the charge resumption voltage level. If the controller has a fully charged LED, it should be off. Record this voltage on the Inspection Record Sheet, page 121.

Step 4: Continue to increase the voltage until the meter reads one-half volt above the charge termination setting of the controller. At this point, the "charging" LED should go off. This is the charge termination voltage level and should be recorded on the Inspection Record Sheet. If the controller has a "fully charged" LED, it should be on.

It may be necessary to use a resistor between the "battery" positive terminal and the "battery" negative terminal to "fool" the charge controller that the battery voltage is high enough to stop charging.

Note: Some charge controllers may not work when the array terminals only are energized. Also note that some controllers break the negative lead in the regulation process.

Step 5: (Use this step if the charge controller has a low voltage load disconnect feature.) Turn the power supply voltage back to zero, then move the meter and power supply to the + and - "battery" terminals on the charge controller. Remove the series resistor if it was previously installed for Step 3.

Slowly increase the voltage. At first, the low voltage disconnect LED may be off. Once you supply enough voltage to operate the controller, but are still below the low voltage disconnect setting, the LED should be on. When the voltage is higher than the disconnect setting, the LED should go off. The voltage at which the LED comes on is the low battery reconnect voltage and should be recorded on the Inspection Record Sheet.

Since many charge controllers have a time delay on load reconnection, it may be necessary to leave the power supply connected for a few minutes. The time required varies with the model of charge controller.

Step 6: Turn the power supply back to zero, then disconnect all the test equipment and wiring. If the charge controller passed the test, follow the correct sequence to reconnect all the system wiring. This sequence varies from model to model, so refer to the manufacturer's information.

Pulse charging

If the charge controller has a pulse charging feature, modify step 4 as follows: Turn the power supply voltage up very slowly. As the voltage approaches the charging termination setting, the controller should start pulse charging.

The controller is trying to pulse voltage into the batteries. The charging LED should be flashing on and off. If the controller has a fully charged LED, it should be off. Note that some controllers pulse so fast that you can not see the flashing of the LED.

Multistage charging

For this test, an ammeter will be needed, as well as the voltmeter. Set the ammeter for the highest setting first, then change settings downward. During the test the current flow will range from amps to milliamps. Connect the ammeter to the controller's "battery" terminals.

Modify step 4 as follows: Turn the power supply voltage up very slowly. At first, the current flow should be a few amps. As the voltage approaches the charging termination setting, the controller should start "trickle" charging at a few hundred milliamps.

Auxiliary generator startup

Charge controllers with a generator startup feature have a set of relay contacts that close to start the generator when the batteries reach a low state of charge. To test this feature, add the following to step 5:

Disconnect the generator starter leads from the generator start terminals. Use the ohmmeter to measure the resistance between the two terminals. The resistance should be zero, indicating that the controller has closed the relay contacts to turn the generator on, whenever the low voltage disconnect LED is on. If the control has a generator start LED indicator, it should also be on at this time. In some systems the generator start LED may come on at a higher voltage than the low battery voltage disconnect setting.

3.1.7 Batteries.

WARNING!

Be extremely careful when working around batteries! Always use eye protection, a face shield, and rubber gloves. Batteries discharge explosive hydrogen gas when charging. Keep cigarettes, sparks, flames, and any other ignition sources away at all times. Always have water and baking soda available to wash off and neutralize acid. Have an eye wash kit immediately available.

FIRST AID INFORMATION

If battery acid should get in your eyes, flush them with water for at least ten minutes and seek immediate medical attention. If acid splashes on your skin, neutralize it immediately with a water and baking soda solution, and flush with plenty of fresh water. If acid is taken internally, drink large quantities of water or milk, follow with milk of magnesia, beaten egg, or vegetable oil, and seek immediate medical attention.

Impact of load

Many battery problems are caused by oversized loads or loads operating for too long. If batteries are in a low state of charge most of the time, check the load as well as the photovoltaic system.

General conditions

WARNING!

Even though the total voltage of battery banks in photovoltaic systems may be low, there can be lethal levels of electrical power present. Use insulated tools, be aware of what you are touching, and "float" yourself. (Keep yourself out of contact with earth ground.)

Label each battery with a number for the battery and numbers for each cell. This insures that the next time the batteries are checked, the same sequence will be used, and results can be compared.

The tops of the batteries should be clean and dry. Caps should all be in place and secure.

All wiring connections should be secure. Look for evidence of corrosion or burning.

Check enclosures, racks, and tie-downs to be sure they are secure and corrosion-free. If the battery enclosure is locked, make sure the lock and hasp are secure. Make sure any insulation of the enclosure is complete and adequate.

Confirm that there are no shelves, hooks, or hangers above the batteries. If a metal tool or other object falls on top of the battery terminals and connections, the results can be catastrophic.

Check the electrolyte level of every cell in every non-sealed battery. It should always be above the top of the plates, but below the tops of the battery cases.

Venting systems <u>must</u> be functional. If the venting system is holes or louvers in the battery box, make sure they are open for air circulation. Screening must be provided to prevent obstruction by vegetation, insects, or animals.

If there is snow in winter, make sure the battery enclosure is high enough off the ground so the snow cannot block the vent. If a fan is used, confirm that it is operating when the batteries are charging.

The freezing points for batteries in various states of charge are shown in Table 2.3 in Section 2. Make sure the batteries are in an environment above these temperatures, and as close to room temperature as possible.

Make sure that a "No Smoking" sign is posted and is highly visible, especially when first entering the area of the batteries.

<u>Determining state of charge</u>

There are four ways to determine the batteries' state of charge. They are listed here in declining order of accuracy.

- Hydrometer/Refractometer
- Actual load test
- Automotive load tester
- Open circuit voltages

Hydrometer

A hydrometer describes the state of charge by determining the specific gravity of the electrolyte. Specific gravity is a measurement of the density of the electrolyte compared to the density of water.

For example, a specific gravity of 1.00 means a particular volume of the electrolyte weighs exactly the same as the same volume of water. A specific gravity of 1.500 would mean it was one and one-half times as heavy as water.

Usually, the specific gravity of electrolyte is between 1.120 and 1.265. At 1.120, the battery is fully discharged. At 1.265, it is fully charged. In temperature extremes, the electrolyte may have been adjusted; lowered for higher temperatures, raised for lower temperatures.

NOTE

Only batteries which use an acid electrolyte can use specific gravity as a measurement of state of charge. The specific gravity of the electrolyte in ni cad batteries does not change with different states of charge.

Differences in density can be measured by the float in a hydrometer. If the battery is fully charged, the electrolyte will be denser. Just as a swimmer floats higher in salt water than fresh water, the hydrometer float, as shown in Figure 3-2, will float higher in an electrolyte sample with a high specific gravity than in one with a low specific gravity.

When using a hydrometer, you are working with strong acid. Wear eye and face protection and rubber gloves. Have baking soda and plenty of fresh water ready to neutralize acid spills. If acid gets in your eyes, rinse them with clean water for 10 minutes and immediately seek medical attention. Flush spilled acid off your skin with large amounts of water. An eye wash kit can be used for both eyes and skin.

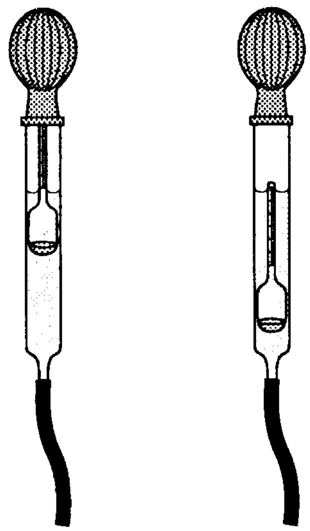


FIGURE 3-2
Hydrometer Float
Positions at Different
States of Charge

Before starting, make a copy of the specific gravity worksheet from the end of this chapter. Fill in the battery and cell numbers on the sheet.

To use a hydrometer, squeeze the bulb while the inlet tube is still above the electrolyte level. Lower the hydrometer into the electrolyte and gradually release the bulb to suck in electrolyte.

When emptying the hydrometer, slowly squeeze the bulb with the inlet just above the electrolyte level, but still inside the battery cell. These methods reduce the chances that electrolyte will spurt out of the battery or the hydrometer.

At the first cell being checked, fill and drain the hydrometer with electrolyte three times before pulling out a sample. This brings the hydrometer to the same temperature as the electrolyte.

Take a sample of electrolyte and allow the bulb to completely expand. The sample must be large enough to completely support the float. Hold the hydrometer straight up and down, so the float is not touching the sides, top, or bottom of the tube.

Look straight across the electrolyte level to read the float, as shown in Figure 3-3. Ignore the curve of electrolyte up onto the sides of the hydrometer. Be careful not to drop the hydrometer or to allow electrolyte to drip out of it.

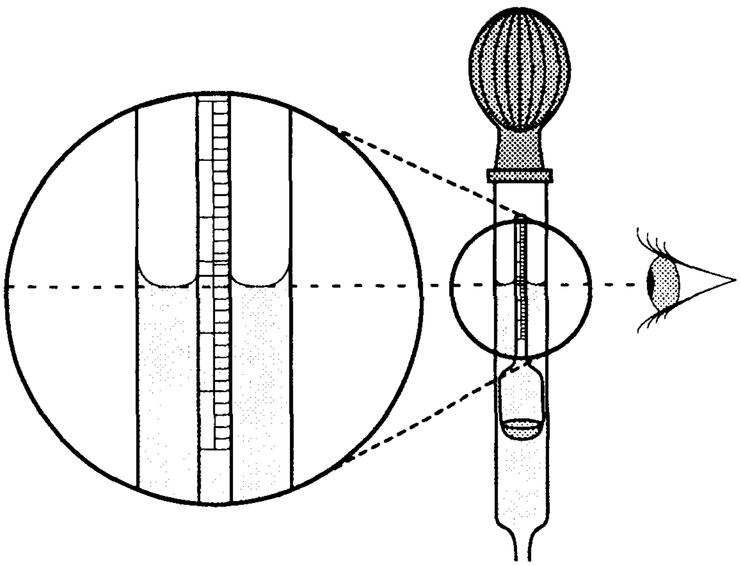


FIGURE 3-3
Reading
a Hydrometer

Record the specific gravity of each cell on a copy of the sheet provided at the end of this chapter.

At the end of testing, rinse the hydrometer out with fresh water at least five times to flush out the acid. Allow it to dry completely before testing again.

CAUTION!

Do not use the same hydrometer for testing lead acid batteries and ni cad batteries. The ni cad batteries will be destroyed by traces of acid.

Since warm fluids are less dense, and cold fluids are denser, some temperature compensation is necessary if the batteries are not at 80°F. The temperature of the electrolyte must be carefully measured.

Some hydrometers have built-in thermometers for this. If not, use an accurate glass thermometer. Immerse only the thermometer bulb into the electrolyte, leave it for five minutes, read it, then rinse it off in clear water.

For every 10°F above or below 80°F, a factor of .004 must be <u>added</u> if the battery is <u>above</u> 80°F, or <u>subtracted</u> if it is <u>below</u> 80°F.

As an example, assume a battery at 100°F has a measured specific gravity of 1.240. The battery is 20°F <u>above</u> the 80°F standard. The compensation is <u>added</u> to the specific gravity.

The compensation to be added is: $.004 \times 2 = .008$

So the corrected specific gravity is: $1.240 + .008 = 1.248$

If the same battery was at 30°F, it is 50° below the 80°F standard, and the compensation is subtracted from the specific gravity.

The compensation to be subtracted is: $.004 \times 5 = .020$

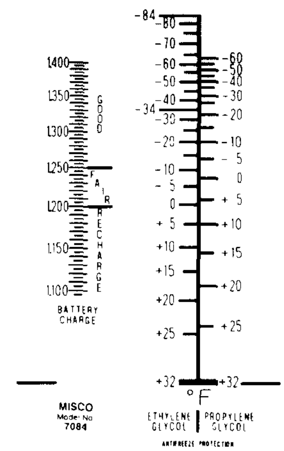
And the corrected specific gravity is: $1.240 - .020 = 1.220$

The refractometer is the most accurate way to measure electrolyte specific gravity. The specific gravity of a liquid will determine how light passes through it and this is the basis of this measurement. A refractometer uses a small amount of fluid and is automatically temperature corrected. These devices are generally compact and rugged. One such device is manufactured by MISCO™ 3401 Virginia Road, Cleveland, Ohio 44122 (NSN #6630-01-345-2884).

Measurement Window

Photos Courtesy of MISCO™

Instrument in Use



Typical Scale Observed During Test

Actual load test

For this test, an accurate DC voltmeter is required.

Operate the system loads from the batteries for five minutes. This will remove any minor "surface charge" the battery plates may have. Turn off the loads and disconnect the batteries from the rest of the system.

Measure the voltage across the terminals of every battery, as shown in Figure 3-4. If external cell connectors are used, measure the voltage across each cell, as shown in Figure 3-5. Do not attempt to measure individual cell voltages unless the connectors are external.

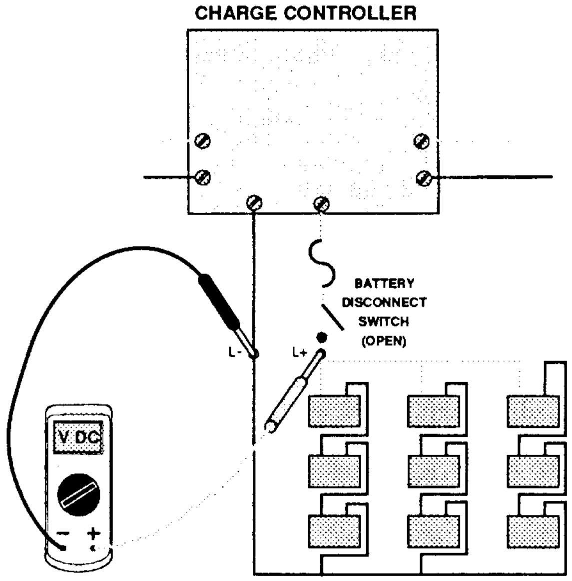


FIGURE 3-4
Measuring the Batteries' Open Circuit Voltage

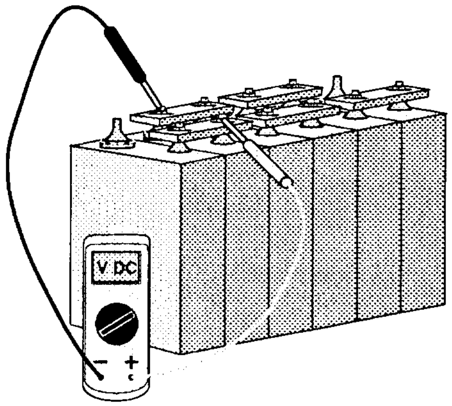


FIGURE 3-5
Measuring the Open Circuit Voltage of Cells with External Connections

TABLE 3-1: Open Circuit Voltages and States of Charge for Deep Cycle Lead Acid Batteries

Open Circuit Voltages			
2 Volt Battery	6 Volt Battery	12 Volt Battery	State of Charge
2.12 or more	6.36 or more	12.72 or more	100%
2.10 to 2.12	6.30 to 6.36	12.60 to 12.72	75-100%
2.08 to 2.10	6.24 to 6.30	12.48 to 12.60	50-75%
2.03 to 2.08	6.90 to 6.24	12.12 to 12.48	25-50%
1.95 to 2.03	5.85 to 6.90	11.70 to 12.12	0-25%
1.95 or less	5.85 or less	11.70 or less	0%

NOTE

These open circuit voltages are for typical deep cycle lead acid batteries appropriate for photovoltaic systems. Automotive batteries, which should not be used, have slightly different voltages at these states of charge.

Reconnect the system again, but leave the array disconnected. Turn on the loads and let them run on battery power for an hour or so. Disconnect the batteries again and remeasure the battery and cell voltages.

If the batteries are in satisfactory condition, the voltages will decline a reasonable amount during this test. For example, if the batteries are supposed to provide stored power through a week of cloudy weather, but running under load for only one hour reduces their state of charge by 50%, one or more of the batteries needs service or replacement.

Record the voltages on a copy of the worksheet at the end of this chapter. Use Table 3-1 to determine the approximate state of charge of the batteries.

Any battery or cell with a voltage more than 10% higher or lower than the average requires service or replacement. Equalization charging, described in Section 6.1.7, may be required. Another indicator is if any battery's voltage varies by 0.05 volts or more per cell from the average, service or replacement is required. As an example, if a 12 volt battery with six cells is 0.3 volts (0.05 x 6) higher or lower than the average voltage of the other batteries, service is required.

Automotive load tester

An accurate DC voltmeter is also necessary for this test.

Instead of running the actual load, an automotive load tester can be connected to the batteries on a 6 or 12 volt system. The advantage of this technique is that a large artificial load can be placed on the batteries for a short period of time, rather than waiting for a relatively small load to slowly drain the batteries of charge.

Remember that at faster rates of discharge, the available battery capacity is reduced. Therefore, this test is not as accurate as a load test done at system's normal rate of discharge.

WARNING!

Some automotive load testers give off sparks or large amounts of heat during operation. The sparks could ignite the hydrogen gas coming from the batteries. The tester may become hot enough to cause serious burns.

Quick load test

An accurate DC voltmeter is also necessary for this test.

Operate the system loads for 15 minutes. This will remove any minor "surface charge" the battery plates may have. Turn off the loads.

Disconnect the batteries from the rest of the system. The measurements of the voltage at the battery terminals are the no load voltages.

Measure the voltage across the terminals of every battery. If external cell connectors are used, measure the voltage across each cell. Do not attempt to measure individual cell voltages unless the connectors are external.

Record the voltages on a copy of the worksheet at the end of this chapter. Use Table 3-1 to determine the approximate state of charge of the batteries.

Any battery or cell with a voltage more than 10% higher or lower than the average requires service or replacement. Another indicator is if any battery's voltage varies by 0.05 volts or more per cell from the average, service or replacement is required. As an example, if a 12 volt battery with six cells is .3 volts (0.05 x 6) higher or lower than the average voltage of the other batteries, service is required. Equalization charging, described in Section 6.1.7, may be required.

3.1.8 Arrays. Check the physical condition of the photovoltaic array. The glass covers should be unbroken and reasonably clean. Module frames should be straight with no serious corrosion. Note any other physical damage or vandalism which has occurred.

All frames, controller chassis, conduit, junction boxes, and other metal components must be electrically tied together and to an earth ground rod driven firmly into the ground. Use an ohmmeter to confirm electrical continuity through the entire equipment grounding system.

In most photovoltaic systems, the negative wiring is bonded to the grounding system. On rare occasions, the equipment powered by the system requires that the negative lines "float," with no connection to earth ground. In this case, a third, grounding conductor is used, as described in Section 2.5.7.

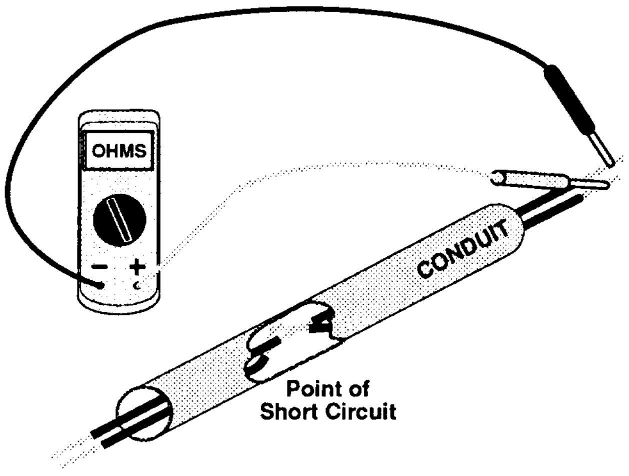
All modules should be unshaded throughout the day. "Spot" shading of a few cells or modules in the entire array must be eliminated.

Check all the mounting hardware for loose fasteners or connections to the mounting surface. Corrosion, rotting, vandalism, or other damage should be recorded for later repair.

Conduit and connections must all be tight and undamaged. Look for loose, broken, corroded, vandalized, and otherwise damaged components. Check close to the ground for animal damage.
If conduit was not used, check cable insulation carefully.

Remove covers to check wiring and wiring connections for similar damage or degradation. Also look for burnt wiring or terminals. If plastic conduit is used, check for a continuous earth ground wire throughout the system.

Confirm that there are no short circuits or ground faults in the system, as shown in Figures 3-6 and 3-7. If the system is off, and all the disconnect switches are open, both these conditions can be found with an ohmmeter.



NOTE: Power Must Be Turned Off For This Test

FIGURE 3-6
Finding a Short Circuit

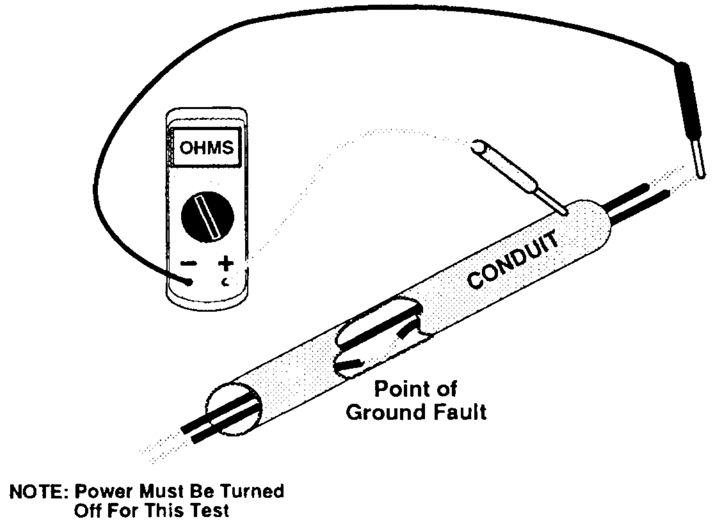


FIGURE 3-7
Finding a Ground Fault

Open circuit voltage

Measure the open circuit voltage of the array. This is done with a DC voltmeter across the Test Points D with the array disconnected from the rest of the system, so the array voltage is measured, not the battery voltage (Figure 3-8).

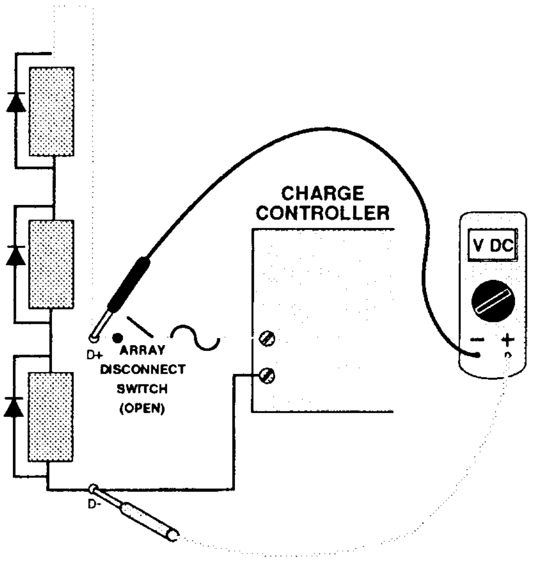


FIGURE 3-8
Measuring the Open Circuit Voltage of the Array

Compare the measured amount of open circuit voltage from the array against the manufacturer's specifications. Remember to multiply the manufacturer's specified voltage times the number of modules in series in the array.

If it has not already been done, label each module in the array with a number.

Measure the open circuit voltage of each module in the array, with the array disconnected from the rest of the system. Use a DC voltmeter across each module's positive and negative terminals when there is no load on the array (Figure 3-9). It is not necessary to disconnect each module from the array.

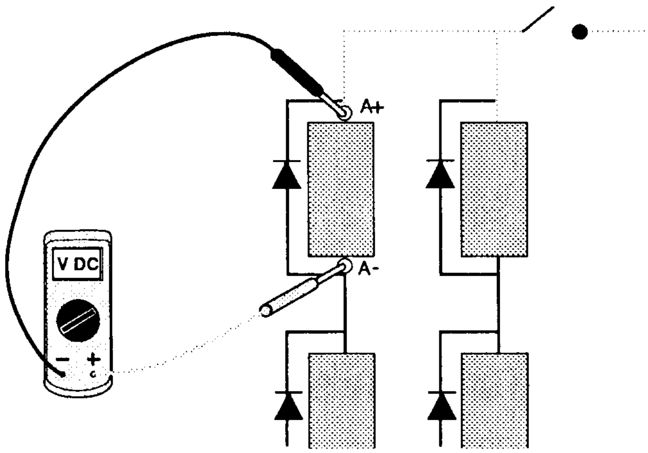


FIGURE 3-9
Measuring the Open Circuit Voltage of a Module

Record each module's voltage on the worksheet at the end of this chapter. Compare the measured open circuit voltage for the modules against the manufacturer's specifications. If any module is 10% or more below the average voltage, also note it on the worksheet.

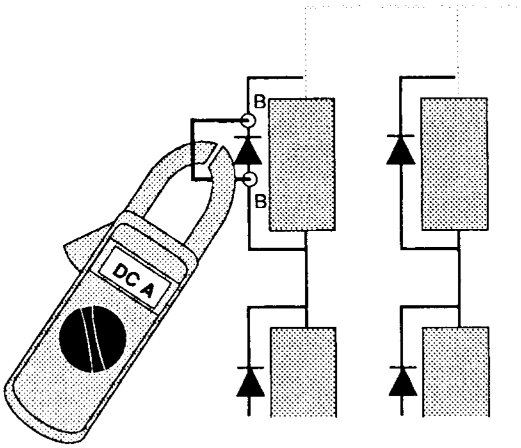
Short circuit current

WARNING!

When measuring the short circuit current of either the modules or the entire array, be careful not to short circuit the battery bank. An explosion can result. To prevent this, open the battery disconnect switch between the short circuit and the batteries.

If your DC meter has leads, connect them to the positive and negative terminals of each module and set the meter to the 10 amp range. If you are using a DC snap around (clamp-on) type of meter, use a short piece of wire to connect the positive and negative terminals of each module, as shown in Figure 3-10. Use the information in Appendix C to determine the appropriate gauge of wire for the anticipated current.

FIGURE 3-10
Measuring a Module's
Short Circuit Current

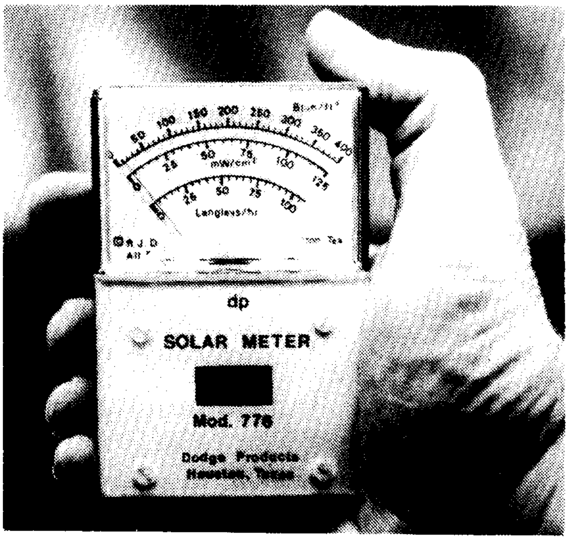


Record the results on the worksheet at the end of this chapter.

Use a solar energy meter to determine how much sunlight is available (Figure 3-11). Compare the measured amount of current from the module against the manufacturer's specifications for that amount of sunlight. Module output current is typically specified at a light level of 1000 watts per square meter and at a temperature of 25°C. The actual operating temperature is usually much higher then 25°C so that the measured output will be lower than the spec calls for.

FIGURE 3-11
A Solar Energy Meter

*Photo Courtesy of
Dodge Products, Inc.*



Record the modules' short circuit current on the worksheet. If the current from any module is 10% or more lower than that from the others, record that as well. Bear in mind that the available sunlight can vary by more than 10% during the testing of a large array, so keep checking the solar energy meter during testing. Also remember that dirty modules put out less current than clean ones.

Reconnect the connections in the array, and short circuit the positive and negative leads of the entire array. Again, use the information in Appendix C to determine an appropriate wire gauge.

Use a snap around DC ammeter again to make the actual measurements, as shown in Figure 3-12. Record the results on the worksheet at the end of this chapter.

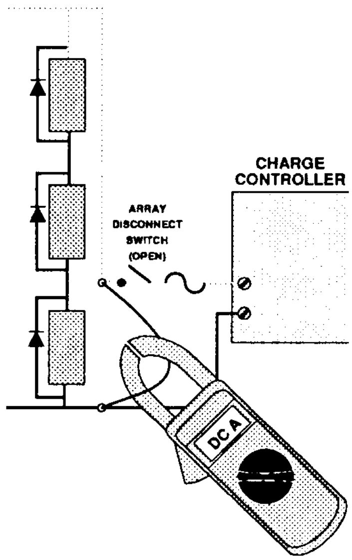


FIGURE 3-12
Measuring an Array's
Short Circuit Current

CAUTION!

The amount of current from the entire array may be much higher than the capacity of a typical DC ammeter. Use the manufacturer's data to make an estimate of the maximum current before making the measurement. Multiply the current per module times the number of modules in series in the array. Start with the highest DC amps scale on the meter, and work down. Be especially careful when making or breaking high current DC circuits. DC arcs are very difficult to extinguish and can cause serious burns and/or damage equipment.

Use a solar energy meter to determine how much sunlight is available. Compare the measured amount of current from the array against the manufacturer's specifications for that amount of sunlight.

3.1.9 DC Loads. Close (turn on) all disconnect switches at this time. Check DC loads to be sure they are operating properly. Look for maintenance needs such as lubrication, cleaning, etc.

Also make sure the loads are the same number, size, and type as originally designed. Many photovoltaic system problems can be traced to added or oversized loads, or loads running too many hours per day.

3.1.10 Inverters. Check the operation of the inverter at the time of the inspection. LEDs should indicate the conditions and operations of the time. Meters, if present, should agree with the readings of portable meters.

A buzz or hum from the inverter is normal.

Make sure the inverter is actually coming on by turning on an AC load. Remember that some inverters have a few seconds of delay when the AC load is turned on and the inverter switches from idling to operating.

Measure and record the current draw of the inverter in both idling and operating states.

Measure and record the voltage drop between the inverter and battery on the positive and negative leg while under load. Measure the current draw simultaneously and use this to calculate the resistance to arrive at the loss between the battery and the inverter.

Check all inverter wiring for loose, broken, corroded, or burnt connections or wires. Look for potential accidental short circuits or ground faults. If not already done, use an ohmmeter to check for these conditions, as described in Section 3.1.8.

The inverter must be in a clean, dry, ventilated, and secure environment. Make sure all these conditions are met, and note any problems of this nature. Racks, tie downs, or enclosures must all be sound.

3.1.11 AC loads. As with DC loads, check AC loads for proper operation. Look for maintenance needs such as lubrication, cleaning, etc.

Also make sure the loads are the same number, size, and type as originally designed. Many photovoltaic system problems can be traced to added or oversized loads, or loads running too many hours per day.

3.2 SAMPLE INSPECTION RECORD SHEETS

3.2.1 Procedures. The next few pages are sample inspection record sheets for use in inspecting photovoltaic systems. Not all the forms can be used for every system, since different inspection methods, particularly those for batteries, use only one technique and thus only one worksheet.

3.2.2 Record of Qualitative Information. By keeping all the filled-out record sheets in a service log for the system, a history of the system will be created. This allows those performing future inspections to review this history, so patterns and trends can be identified and anticipated.

For example, if several consecutive inspections find evidence of animal damage to conduit and wiring, closer attention can be paid to looking for the same type of damage again. This more detailed search may turn up problems that would otherwise go undetected. This can prevent an unanticipated system failure later.

3.2.3 Record of Quantitative Information. The same type of historical perspective can be used by future inspectors and troubleshooters to detect patterns of gradual performance decline.

A complete system history can reduce the time required to find system faults, since service personnel can focus first on the most likely problems.

3.2.4 Save with Other System Documentation. None of the filled-out record sheets will ever help if they are not available to future service personnel. Keep all system documentation in one place. The best place for storage is at the maintenance shop, bringing it to the site when inspections are done.

If the most likely system problems are known, the proper tools and materials can be brought to the site at first, rather than making another trip.

SAMPLE INSPECTION WORKSHEET

Inspection performed by: ______________________________ Date:

Permission to disconnect critical loads given by:

Name: ______________________________ Title: ______________________________

System Meters

Service Required?

Yes	No		System Meter	Portable Meter
☐	☐	Array voltage:	____________	____________
☐	☐	Battery voltage:	____________	____________
☐	☐	Array current:	____________	____________
☐	☐	Load current:	____________	____________

LED and Other Indicators

Service Required?			Status of Indicators	
Yes	No		On	Off
☐	☐	Charging	___	___
☐	☐	Fully charged	___	___
☐	☐	Low voltage disconnect	___	___

Portable Metering

Service Required?

Yes No

☐ ☐ Battery voltage (total): ______________________

☐ ☐ Charging current: ______________________

☐ ☐ Grounding system has continuity?

Disconnect Switches

Service Required? Yes	No		Upon Arrival: Installed	On (closed)	Off (open)
☐	☐	Array	☐	☐	☐
☐	☐	Battery bank	☐	☐	☐
☐	☐	Polarity correct			

OPEN ALL DISCONNECT SWITCHES NOW

System Wiring

Service Required?
Yes No

☐ ☐ Disconnect switches in place and open
☐ ☐ No short circuits
☐ ☐ No ground faults
☐ ☐ Wire color code conventions correct
☐ ☐ No arc damage to switches, circuit breakers, or relays
☐ ☐ No damage to conduit or wire insulation
☐ ☐ No damaged or loose wiring connections

Describe location of deficiencies ____

____

Charge Controller

Service Required?
Yes No

☐ ☐ Controller and area clean
☐ ☐ Controller securely mounted
☐ ☐ Ambient temperature in appropriate range
☐ ☐ Controller not installed in sealed area with batteries
☐ ☐ Optional operational test for shunt charge controllers
DC voltage from array: ____________________
DC voltage to battery: ____________________
☐ ☐ Optional operational test for series-relay controllers
Step #
☐ ☐ 3 Charge resumption voltage level: ________________
☐ ☐ 4 Charge termination voltage level: ________________
☐ ☐ 5 Low battery voltage reconnect voltage level: ________________

Batteries

Service Required?
Yes No

☐ ☐ Loads correct size, schedule, and type
☐ ☐ Batteries and cells numbered
☐ ☐ Battery tops clean and dry
☐ ☐ All caps secure
☐ ☐ Battery interconnections secure, corrosion-free, and coated with anti-oxidant
☐ ☐ Racks and tie-downs secure and in good condition
☐ ☐ Enclosure and insulation secure and in good condition
☐ ☐ No shelves, hooks, or hangers above batteries
☐ ☐ Electrolyte levels adequate*
☐ ☐ Venting system operating properly and unobstructed
☐ ☐ Ambient temperature in appropriate range
☐ ☐ No Smoking sign prominently posted

* If electrolyte levels are low, make a note of which battery cells require water on either the "Specific Gravity" or "Open Circuit Voltage" worksheets which follow.

SPECIFIC GRAVITY RECORD

Electrolyte temperature: ________________°F

Temperature correction applied to each measurement: ☐ + __________ or
☐ - __________

BATTERY OPEN CIRCUIT VOLTAGE RECORD

(APPLY THE TEMPERATURE CORRECTION TO THE MEASURED SPECIFIC GRAVITY BEFORE RECORDING IT ON THIS SHEET.)

Battery # ___	Specific Gravity or Voltage	Battery # ___	Specific Gravity or Voltage
Cell # 1	________	Cell # 1	________
Cell # 2	________	Cell # 2	________
Cell # 3	________	Cell # 3	________
Cell # 4	________	Cell # 4	________
Cell # 5	________	Cell # 5	________
Cell # 6	________	Cell # 6	________

Battery # ___	Specific Gravity or Voltage	Battery # ___	Specific Gravity or Voltage
Cell # 1	________	Cell # 1	________
Cell # 2	________	Cell # 2	________
Cell # 3	________	Cell # 3	________
Cell # 4	________	Cell # 4	________
Cell # 5	________	Cell # 5	________
Cell # 6	________	Cell # 6	________

Battery # ___	Specific Gravity or Voltage	Battery # ___	Specific Gravity or Voltage
Cell # 1	________	Cell # 1	________
Cell # 2	________	Cell # 2	________
Cell # 3	________	Cell # 3	________
Cell # 4	________	Cell # 4	________
Cell # 5	________	Cell # 5	________
Cell # 6	________	Cell # 6	________

Battery # ___	Specific Gravity or Voltage	Battery # ___	Specific Gravity or Voltage
Cell # 1	________	Cell # 1	________
Cell # 2	________	Cell # 2	________
Cell # 3	________	Cell # 3	________
Cell # 4	________	Cell # 4	________
Cell # 5	________	Cell # 5	________
Cell # 6	________	Cell # 6	________

Arrays

Service Required?
Yes No

- ☐ ☐ Glass covers clean and unbroken
- ☐ ☐ All module frames and mounting hardware earth grounded
- ☐ ☐ Negative wiring grounded in two-wire DC system, or
- ☐ ☐ Negative wiring floating in three-wire DC system
- ☐ ☐ All cells in all modules unshaded all day
- ☐ ☐ Mounting hardware secure and in good condition
- ☐ ☐ Conduit and connections secure and in good condition
- ☐ ☐ All wiring and connections secure and in good condition
- ☐ ☐ No short circuits
- ☐ ☐ No ground faults
- ☐ ☐ All modules numbered
- ☐ ☐ Open circuit voltage of array (positive to negative): ______________
- ☐ ☐ Open circuit voltage of array (positive to ground): ______________
- ☐ ☐ Open circuit voltage of array (negative to ground): ______________
- ☐ ☐ All modules open circuit voltages within 10% of each other*
- ☐ ☐ Short circuit current of array: ______________
- ☐ ☐ All modules short circuit current within 10% of each other*

* Modules not within 10% of average voltage: ______________________________

____

* Modules not within 10% of average current (with allowances for variations in sunlight intensity): ____

____

ARRAY OPEN CIRCUIT VOLTAGE RECORD

String # ___	Total Voltage ________	String # ___	Total Voltage ________
Module # 1	________	Module # 1	________
Module # 2	________	Module # 2	________
Module # 3	________	Module # 3	________
Module # 4	________	Module # 4	________
Module # 5	________	Module # 5	________
Module # 6	________	Module # 6	________

String # ___	Total Voltage ________	String # ___	Total Voltage ________
Module # 1	________	Module # 1	________
Module # 2	________	Module # 2	________
Module # 3	________	Module # 3	________
Module # 4	________	Module # 4	________
Module # 5	________	Module # 5	________
Module # 6	________	Module # 6	________

ARRAY SHORT CIRCUIT CURRENT RECORD

String # ___	Total Current ________	String # ___	Total Current ________
Module # 1	________	Module # 1	________
Module # 2	________	Module # 2	________
Module # 3	________	Module # 3	________
Module # 4	________	Module # 4	________
Module # 5	________	Module # 5	________
Module # 6	________	Module # 6	________

String # ___	Total Current ________	String # ___	Total Current ________
Module # 1	________	Module # 1	________
Module # 2	________	Module # 2	________
Module # 3	________	Module # 3	________
Module # 4	________	Module # 4	________
Module # 5	________	Module # 5	________
Module # 6	________	Module # 6	________

DC Loads

Service Required?
Yes No

☐ ☐ Loads correct size, schedule, and type
☐ ☐ Loads require maintenance or repair

Inverter

Service Required?
Yes No

☐ ☐ Proper operation at time of inspection
☐ ☐ System meter readings agree with portable meters
☐ ☐ Normal inverter sound
☐ ☐ Inverter switches from idling to operating
☐ ☐ All wiring secure and in good condition
☐ ☐ No short circuit conditions
☐ ☐ No ground fault conditions
☐ ☐ Inverter and area are clean, dry, and ventilated
☐ ☐ Racks and enclosures secure and in good condition

AC Loads

Service Required?
Yes No

☐ ☐ Loads correct size, schedule, and type
☐ ☐ Loads do not require maintenance or repair

RECONNECT ALL WIRING AND CLOSE ALL DISCONNECT SWITCHES NOW

3.3 QUESTIONS FOR SELF-STUDY

Directions: Choose the best answer to each question.

1) When plastic conduit is used for DC photovoltaic wiring, which of the following is required?

   A) The conduit must be buried
   B) A ground wire must be run outside the conduit, taped at two-foot intervals
   C) A ground wire must be run inside the conduit
   D) The conduit must be airtight

2) Which of the following will significantly affect the array voltage?

   A) The number of modules in series
   B) The amount of sunlight
   C) The array tilt angle
   D) The number of modules in parallel

3) Where should the charge controller be installed?

   A) In a dry, sheltered location
   B) In the battery enclosure
   C) Facing the same direction and at the same tilt as the modules
   D) None of the above

4) When should a pulse charger start pulsing?

   A) As the voltage drops, approaching the load disconnect setting
   B) As the voltage rises above the load disconnect setting
   C) As the voltage drops, approaching the charge termination setting
   D) As the voltage rises, approaching the charge termination setting

5) If battery acid is taken internally, which of the following should be done?

   A) Drink large quantities of water or milk
   B) Follow with milk of magnesia, beaten egg, or vegetable oil
   C) Seek medical attention immediately
   D) All of the above

6) Why should there be no shelves or hooks above battery banks?

A) They interfere with air circulation
B) Objects could fall on the battery connections
C) Shelves, hooks, or objects on them could be damaged by acid fumes
D) They could obstruct the view of the battery bank

7) What does a hydrometer measure?

A) Specific gravity
B) Relative humidity
C) Temperature
D) Enthalpy

8) A 12 volt lead acid battery with an open circuit voltage of 12.3 has which state of charge?

A) 0-25%
B) 25-50%
C) 50-75%
D) 75-100%

9) Ground faults can be found with what type of meter?

A) Ammeter
B) Voltmeter
C) Ohmmeter
D) Wattmeter

10) Burnt, corroded, or damaged connections may be present at:

A) The charge controller
B) The inverter
C) The system disconnect switches
D) All of the above

4.0 TROUBLESHOOTING

What You Will Find In This Chapter

This chapter contains information on determining what is wrong with a photovoltaic system. Troubleshooting charts for various system components are included.

It is assumed you understand basic electrical concepts, and can use an electrical meter to measure voltage, current, and resistance.

Information on normal system operation can be found in Chapter 2, Operation. Similarly, repair and preventative maintenance operations are described in Chapters 5 and 6. You should be familiar with the inspection procedures covered in Chapter 3. Review copies of the inspection record sheet for the system you will be troubleshooting.

The first part of this chapter explains fundamental troubleshooting techniques for photovoltaic systems. If you are unfamiliar with troubleshooting operations, read this information carefully.

Figure 4-1 shows the system test points referred to throughout this chapter.

The lists in Appendix A detail the tools and materials you will need to perform troubleshooting operations.

4.1 TROUBLESHOOTING METHODS

4.1.1 Planning. Before going to the site of a photovoltaic system, plan your course of action.

Photovoltaic systems have two characteristics that have an impact on planning. First, many are in remote locations that take a long time to reach. Second, they may provide power for critically important loads. Minimizing the amount of time these loads are without power may be very important.

If possible, make some educated guesses about what the problem is. Don't dismiss less likely possibilities, but if you think the problem is probably in a particular component, be sure to bring a spare of that component. Ask the inspector or user of the system about its symptoms.

Think about what tools and other materials you know you will need, as well as the ones you might need. Estimate the amount of time you think it will take to determine what the problem is. If you are also responsible for repair operations, estimate the time required for correcting system deficiencies.

4.1.2 Permission to Disconnect Critical Loads. Many photovoltaic systems power critical loads, such as communication systems, warning lights, and others. Be sure to get permission from the proper authority to disconnect such loads before doing so. In some cases, an auxiliary power supply may be necessary to operate the load while troubleshooting the photovoltaic system.

4.1.3 Checking. Checking the system is at the center of troubleshooting. Check out the most likely possibilities first. In this manual's troubleshooting charts, the most likely cause for a particular symptom is listed first. Then, in declining order of likelihood, the other causes are listed. The charts themselves follow the same ranking of likelihood.

Don't hesitate to follow your own intuition regarding what the most likely cause is. This is especially true if you are personally familiar with the history of the system, or your predecessors kept a complete and accurate log of the service performed on the system.

Proceed logically through various possible causes. Perform one test, finish it, then perform the next. If you are trying three things at once and suddenly the system comes back to life, you may never know what the problem really was.

Other than oversize loads and poor wiring connections, most photovoltaic repair operations are actually replacement operations. For this reason, "troubleshooting by replacement" is a perfectly valid way to find out what is wrong with a system.

For example, replacing a suspicious charge controller with a new one that you know is operating correctly is probably the quickest way to determine if the original charge controller was operating properly. In addition, the replacement has already been done, so the service work is performed more rapidly.

4.1.4 Seek Cause, not Symptom. On the other hand, you must determine the real cause of a problem. Although sometimes components simply fail, there may be another defect in the system that causes repeated failures of the same kind to the same system component.

For example, if a system was installed with too many modules in parallel, the current flow might be too high for a particular charge controller. While it is possible to continue replacing the fuse in the controller, or the controller if it is not fused, it makes more sense to change to a controller with a higher current rating.

4.1.5 Don't Stop with One Problem. There is also the possibility that the system has more than one problem. Do not consider the system operational again until the entire system has been fully checked out. The basic inspection steps outlined in the inspection worksheet in the previous chapter should be followed before leaving the site, to be sure another defect is not overlooked.

4.1.6 Testing Replaced Components. Unless a test at the site positively identifies the defect in a component, it should be tested once it is out of the field. Testing can be done in the shop or by the equipment manufacturer, but a determination of the failure mode is important.

Knowing what failed usually leads to identifying and avoiding the conditions which caused the failure. This will improve the reliability of the system with the defective component, and other similar systems.

4.1.7 Keeping Records. The information gained from troubleshooting and testing failed components is lost without complete and accurate records. A review of previous service operations for a particular system is one of the best ways to plan future operations.

WARNING!

Even at the low voltages typically used, photovoltaic battery banks and photovoltaic arrays both contain lethal amounts of current! Photovoltaic arrays make electricity whenever light shines on them. Modules can only be "turned off" by covering them with an opaque material, facing them to the ground, or working at night.

Lead acid batteries are filled with high concentration sulfuric acid and give off explosive hydrogen gas while charging. Wear proper eye and skin protection, have baking soda and water available for emergencies, and do not smoke or use fire or spark sources near batteries.

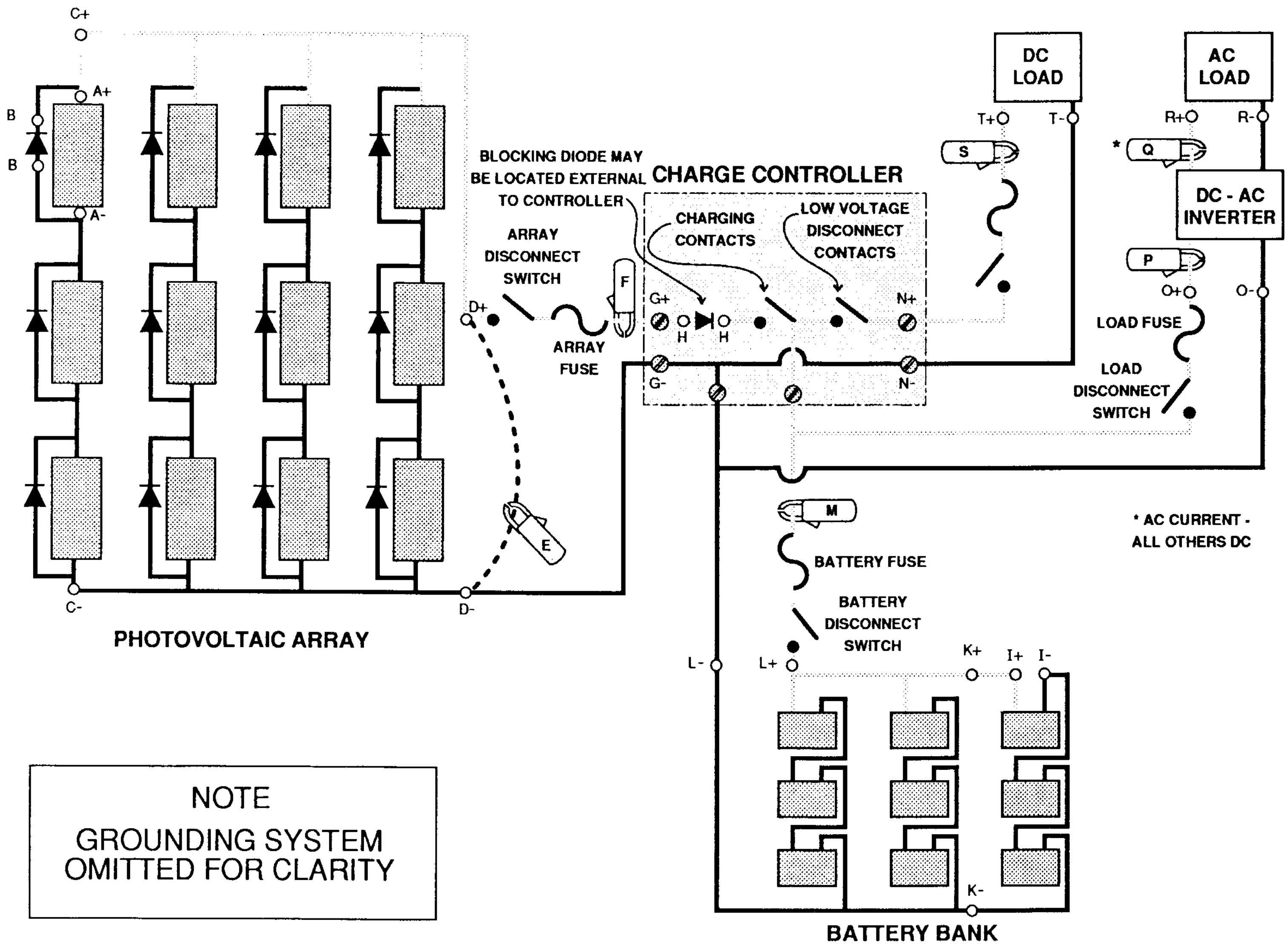


FIGURE 4-1
Photovoltaic System Test Points

4.2 TROUBLESHOOTING TABLES

How to use these tables

The usual reason for troubleshooting a photovoltaic system is a load that doesn't work or is operating improperly. If the load is not defective, some part of the photovoltaic system may be. The user may not understand the limitations of a photovoltaic system.

If you have a good idea of where the problem is, turn to the table for that component. If not, use Table 4-1. This table suggests which of the other troubleshooting tables to use, and which order to use them in.

This allows you to start at the most likely source of a particular problem. Don't forget to completely check out the system before leaving, however.

The tables are organized, as much as possible, with the most likely problems listed first. The tables themselves are presented in order of likelihood. The tables are:

Table 4-1 Directory of Troubleshooting Tables
Table 4-2 Troubleshooting Wiring, Switches, and Fuses
Table 4-3 Troubleshooting Loads
Table 4-4 Troubleshooting Batteries with Low Voltage
Table 4-5 Troubleshooting Batteries that Will Not Accept a Charge
Table 4-6 Troubleshooting Batteries with High Voltage
Table 4-7 Troubleshooting Charge Controllers
Table 4-8 Troubleshooting Inverters
Table 4-9 Troubleshooting Arrays

Before using Table 4-1, measure the battery voltage at test points B, and array voltage at test points E. Compare these voltages to the design voltages.

TABLE 4-1: Directory of Troubleshooting Tables

If:	The most helpful tables are:
Battery voltage is low.	4-2, 4-3, 4-4, 4-5, 4-7
Batteries will not accept a charge.	4-2, 4-3, 4-5
Battery voltage is high.	4-6, 4-7
Load does not operate at all.	4-2, 4-3, 4-8
Load operates poorly.	4-2, 4-3, 4-5, 4-7, 4-8
Array voltage is zero.	4-2, 4-7, 4-9
Array voltage is low.	4-2, 4-9

TABLE 4-2: Troubleshooting System Wiring, Switches, and Fuses

Symptom:	Cause:	Result:	Action:
Load does not operate at all	Switches in the system are turned off or are in the wrong position	Photovoltaic electricity cannot be supplied to loads or batteries	Put all switches in correct position.
	System circuit breakers or fuses are blown		Reset circuit breaker or replace fuse*
Load operates poorly or not at all	There is a high voltage drop in the system Check for undersized or too-long wiring, over-sized loads, a ground fault, or a defective diode	Inadequate voltage to charge batteries or operate loads	Increase wire size, reduce load size, find and correct ground faults
	Wiring or connections are loose, broken, burned, or corroded		Repair or replace damaged wiring or connections
	Wiring or connections are short-circuited or have a ground fault		Repair short circuits or ground faults

*Determine <u>why</u> fuses or circuit breakers blew or tripped before replacing or resetting them

TABLE 4-3: Troubleshooting Loads

Symptom:	Cause:	Result:	Action:
Load does not operate at all	Load is too large for the system, or inadequate sun	Shortened battery life, possible damage to loads	Reduce load size or increase array or battery size
	The load is turned off inadvertently. Check for load switches shut off, blown fuses or tripped breakers, tripped motor thermal breaker, or an unplugged line cord	Load does not operate	Repair or replace load* Reset switches
	The load is in poor condition. Check for short circuits in load, a broken load, or an open circuit in the load	Shortened battery life, possible further damage to loads	Repair or replace load Check load manufacturer for service information
Load operates poorly or not at all	There is inadequate voltage at load. Check for undersized or too-long wiring, oversized loads, or a ground fault	Inadequate voltage to charge batteries or operate loads	Increase wire size, reduce load size, find and correct ground faults
	Wiring or connections are loose, broken, burned, or corroded		Repair or replace damaged wiring
	Small, "phantom" load keeps inverter idling, draining battery		Turn off phantom load or replace it with one not requiring photovoltaic power
	Wiring polarity is reversed	Loads operate backwards or not at all	Correct wiring polarity

*Determine why fuses or circuit breakers blew or tripped before replacing or resetting them

TABLE 4-4: Troubleshooting Batteries with Low Voltage

Symptom:	Cause:	Result:	Action:
No apparent battery defect	Load too large, on too long, or inadequate sun	Battery is always at a low state of charge	Reduce load size or increase system size
	Batteries too cold	A higher voltage is required to reach full charge	Insulate battery enclosure, bury enclosure in ground, move to heated space, install controller with temperature compensation, or repair or replace probe
Low electrolyte level	Overcharging	Loss of battery capacity See Table 4-5 for further information	Add distilled water, unless batteries damaged beyond repair
Battery will not accept a charge	Damaged battery	See Table 4-5 for further information	
Voltage below charging resumption setting	Faulty charge controller	Excessive discharge depth See Table 4-5 for further information	Adjust settings or repair or replace charge controller
Voltage below low voltage disconnect setting	Faulty charge controller	Excessive discharge depth See Table 4-5 for further information	Adjust settings or repair or replace charge controller
Voltage loss overnight even when no loads are on	Faulty blocking diode	Reverse current flow at night discharging batteries	Replace diode
Voltage increasing very slowly, even when no loads are on	Controller not in full charge, stuck in float charge	Inadequate current flow to fully charge batteries	Repair or replace charge controller
Voltage not increasing even when no loads are on and system is charging	Otherwise faulty charge controller	No power from array going into batteries	Repair or replace charge controller
	Switch, circuit breaker, or fuse open, tripped, or blown	No power from array going into batteries	Close switch, reset circuit breaker*, or replace fuse*
	Loose, corroded, or broken wiring	Less power from array going into batteries	Repair or replace damaged wiring
	Shaded modules, broken cell, or misoriented modules	Array output reduced	Remove source of shading, replace module, or correct module orientation
	Wiring too long or undersized	Voltage reduced	Increase wire size
Voltage just above charge resumption setting, but controller not charging batteries	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are cooler than their actual temperature	Repair, replace, or reposition probe
Inaccurate charge controller dial	Misadjusted charge controller		Reset controller dial or replace controller

*Determine why fuses or circuit breakers blew or tripped before replacing or resetting them

TABLE 4-5: Troubleshooting Batteries That Will Not Accept a Charge

Symptom:	Cause:	Result:	Action:
No apparent battery defect	Load too large, on too long, or inadequate sun	Battery is always at a low state of charge	Reduce size of load or increase size of system
High water loss	Overcharging	Heat damage to plates and separators	Replace battery, repair or replace charge controller
Electrolyte leakage shorts	Broken/leaking container	Sulfation, lead sulfate	Replace battery
Muddy electrolyte material, shorts between plates	Age	Shedding of plate	Replace battery
Discolored or odorous electrolyte	Contaminated electrolyte	Battery failure	Replace battery
No symptoms other than not accepting a charge*	Undercharging, usually without adding water	Sulfation, possibly lead sulfate shorts between plates	Replace battery
	Left uncharged too long long	Sulfation, or plates hard when scratched	Replace battery
	Cracked partition between cells	Discharge between adjacent cells	Replace battery
	Hammering cable connections on to terminal posts	Shorts between terminal post strap and plates, electrolyte leak	Replace battery
	Misaligned plates and separators	Treeing shorts between bottoms of plates	Replace battery
	Plate material carried to top of plates	Mossing shorts between tops of plates	Replace battery
	Shorts between plates and straps	Grid top broken and moved upward to strap, lead rundown from strap to plate	Replace battery
	Overcharging a sulfated plate	Spalling (shedding of chunks of plate material)	Replace battery
	Overcharging	Disintegration of positive plates	Replace battery
	Specific gravity and temperature too high for too long	Soft negative plates	Replace battery
	Too many shallow charging cycles	Cracked negative plates	Replace battery
	Holes in separators	Loose fragment of grid, buckled plates, lumps or dendrites on plate, weak spot in separator, vibration	Replace battery

* Although the battery damage from these causes cannot be seen without taking apart the battery, they are listed here for the sake of completeness. Do not attempt to dismantle batteries!

TABLE 4-6: Troubleshooting Batteries with High Voltage

Symptom:	Cause:	Result:	Action:
Voltage over charge termination setting and/or high water loss	Faulty or nonexistent charge controller	Shortened battery life, possible damage to loads	Replace with charge controller with lower charge termination setting
	Battery storage too small for array	Shortened battery life, possible damage to loads and batteries	Install more batteries
	Misadjusted charge controller	Shortened battery life, possible damage to loads and batteries	Adjust charge controller
	Mismatched battery and voltage regulator	Shortened battery life, possible damage to loads and batteries	Replace charge controller, or change setting on adjustable units
	Batteries are cold and charge controller has temperature compensation	Shortened battery life, possible damage to loads	Insulate batteries, or move to warm environment
High water loss	Batteries are too hot	Voltage at which gassing starts is lower than normal	Insulate battery enclosure, and/or provide ventilation
	Infrequent maintenance	Low water levels, battery damage	Shorten maintenance interval
Voltage only slightly above charge termination setting	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are warmer than their actual temperature	Repair, replace, or reposition probe

TABLE 4-7: Troubleshooting Charge Controllers

Symptom:	Cause:	Result:	Action:
Battery voltage below charge resumption setting	Faulty charge resumption function in charge controller	Excessive battery discharge See Table 4-5 for further information	Repair, readjust, or replace charge controller
Battery voltage just below charge resumption setting, but controller not charging batteries	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are cooler than their actual temperature	Repair, replace, or reposition probe
Battery voltage below low voltage disconnect setting	Faulty low voltage cutoff in charge controller	Excessive battery discharge See Table 4-5 for further information	Repair or replace charge controller
Battery voltage loss overnight even when no loads are on	Faulty blocking diode, no diode, or faulty charge controller	Reverse current flow at night, discharging batteries	Replace or add diode, or repair or replace series relay charge controller
	Old or faulty batteries	Batteries self-discharging	Replace batteries

TABLE 4-7: Troubleshooting Charge Controllers (continued)

Symptom:	Cause:	Result:	Action:
Battery voltage not increasing even when no loads are on and system is charging	Otherwise faulty charge controller	No power from array going into batteries	Repair or replace charge controller
Battery voltage over charge termination setting and/or high water loss (See Table 2-5)	Faulty or nonexistent charge controller	Shortened battery life, possible damage to loads and batteries	Repair or replace charge controller and possibly batteries
	Misadjusted charge controller	Shortened battery life, possible damage to loads and batteries	Repair or replace charge controller and possibly batteries
	Mismatched battery and voltage regulator	Shortened battery life, possible damage to loads and batteries	Change charge controller, or change setting on adjustable units
	Controller always in full charge, never in float charge	Shortened battery life, possible damage to loads	Repair or replace charge controller and possibly batteries
Battery voltage just above charge termination setting, but controller still charging batteries	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are warmer than their actual temperature	Repair, replace or reposition temperature probe or change charge controller
Buzzing relays	Too few batteries in series	Voltage is low	Reconfigure or add batteries
	Loose or corroded battery connections	High voltage drop	Repair or replace cables
	Low battery voltage	See Table 4-4 for more information	Repair or replace batteries
Erratic controller operation and/or loads being disconnected improperly	Timer not synchronized with actual time of day	Controller turns on and off at wrong times	Either wait until automatic reset next day, or disconnect array, wait 10 seconds, and reconnect array
	Electrical "noise" from inverter	Rapid on and off cycling	Connect inverter directly to batteries, put filters on load
	Low battery voltage	See Table 4-4 for more information	Repair or replace batteries
Erratic controller operation and/or improper load dis-connection	Faulty or mispositioned temperature probe or poor connection at "battery sense" terminals on charge controller	Charge controller thinks batteries are warmer or cooler than their actual temperature	Repair, reposition, or replace temperature probe or change charge controller
	High surge from load	Battery voltage drops during surge	Use larger wire to load, or add batteries in parallel
	Otherwise faulty charge controller, possibly from lightning damage	Loads disconnected improperly, other erratic operation	Repair or replace charge controller and check system grounding

TABLE 4-7: Troubleshooting Charge Controllers (continued)

Symptom:	Cause:	Result:	Action:
Erratic controller operation and/or improper load dis-connection (cont.)	Adjustable low voltage disconnect set incorrectly	Loads disconnected improperly	Reset low voltage setting
	Load switch in wrong position on controller	Loads never disconnect	Reset switch to correct position
	Charge controller has no low voltage disconnect feature	Loads never disconnect	If necessary, replace charge controller with one with a low voltage disconnect feature
Fuse to array blows	Array short circuited with batteries still connected	Too much current through charge controller	Disconnect batteries when testing array's short circuit current
	Current output of array too high for charge controller	Too much current through charge controller	Replace charge controller with one with a higher rating
Fuse to load blows	Short circuit in load	Unlimited current	Repair short circuit or replace load
	Current draw of load too high for charge controller	Too much current through charge controller	Reduce load size or increase charge controller size
	Surge current draw of load too high for charge controller	Too much current through charge controller	Reduce load size or increase charge controller size
"Charging" at night	Normal operation for some charge controllers up to two hours after dark	No appreciable energy loss	Check the system later that night
	Timer not synchronized with actual time of day	Controller turns on and off at wrong times	Either wait until automatic reset next day, or disconnect array, wait 10 seconds, and reconnect

TABLE 4-8: Troubleshooting Inverters

Symptom:	Cause:	Result:	Action:
No output from inverter	Switch, fuse, or circuit breaker open, blown, or tripped, or wiring broken or corroded	No power can move through inverter	Close switch, replace or reset fuse* or circuit breaker*, or repair wiring or connections
	Low voltage disconnect on inverter or charge controller open	No power available to inverter	Allow batteries to recharge
	Time delay on inverter startup from idle	Few second delay after starting load	Wait a few seconds after starting loads
	High battery voltage disconnect on inverter open	Inverter does not start	Connect load to batteries and operate it long enough to bring down battery voltage Adjust high voltage disconnect on charge controllers

TABLE 4-8: Troubleshooting Inverters (continued)

Symptom:	Cause:	Result:	Action:
Motors running hot	Square wave inverter used	Harmonics of waveform rejected as heat	Change to DC motors or use inverter with quasi-sine or sinusoidal waveform
Loads operating improperly	Excessive current draw by load	Voltage from inverter too low for load	Reduce size of loads or replace inverter with one of larger capacity
	Square wave inverter used		Change to DC motors or use inverter with quasi-sine or sinusoidal waveform
	Defective inverter		Replace inverter
Motors operating at wrong speeds	Inverter not equipped with frequency control	AC frequency varies with battery voltage	Replace inverter with one equipped with frequency control
Inverter circuit breaker trips	Load operating or surge current too high	Excessive current draw by load	Reduce size of loads or replace inverter with one of larger capacity
Inverter DC circuit breaker trips	Inverter capacitors not charged up on initial startup	Excessive current draw by inverter	Install momentary contact switch and 15 ohm, 50 watt resistor in parallel with the circuit breaker, use it for a few seconds to charge capacitors on first start up

*Determine why fuses or circuit breakers blew or tripped before replacing or resetting them

TABLE 4-9: Troubleshooting Arrays

Symptom:	Cause:	Result:	Action:
No current from array	Switches, fuses, or circuit breakers open, blown or tripped, or wiring broken or corroded	No current can flow from array	Close switches, replace fuses*, reset circuit breakers*, repair or replace damaged wiring
Array current low	Some modules shaded		Remove source of shading
	Some array interconnections broken or corroded	Drop in output current	Repair interconnections
	Defective bypass or blocking diodes	Drop in output current	Replace defective diodes
	Some modules damaged or defective	Drop in output current	Replace affected modules
	Full sun not available	Drop in output current	Wait for sunny weather
	Modules dirty	Drop in output current	Wash modules
	Array tilt or orientation incorrect	Drop in output current	Correct tilt and/or orientation

TABLE 4-9: Troubleshooting Arrays (continued)

Symptom:	Cause:	Result:	Action:
No voltage from array	Switches, fuses, or circuit breakers open, blown or tripped, or wiring broken or corroded	No power can move from array	Close switches, replace fuses*, reset circuit breakers*, repair or replace damaged wiring
Array voltage low	Some modules in series with others disconnected or bypass diodes defective	Drop in array voltage	Repair or replace modules, connections, or diodes
	Wiring from array to balance of system undersized or too long	Drop in array voltage	Replace undersized wiring

*Determine why fuses or circuit breakers blew or tripped before replacing or resetting them

4.3 TROUBLESHOOTING PROCEDURES

NOTE

More detailed information on checking system components is in Chapter 3, Inspection. Even if the defect in a system is apparently in one system component, perform the complete system inspection described in Chapter 3. System test points are shown in Figure 4-1, which is the same as Figure 3-1.

4.3.1 System Wiring, Switches, and Fuses. Visually check all wiring connections, switches, circuit breakers, and fuses. Check crimp terminals for solid connections by pulling on wires. Large cartridge fuses do not look different when they are blown. Remove these and use an ohmmeter to check their continuity. An infinite reading means the fuse is blown. A zero reading means it is still intact.

Determine why a fuse or circuit breaker blew or tripped before replacing or resetting it.

Check the voltage drop in the system from the array connections to the loads. To do this, use a DC voltmeter to measure the voltage at test points D, then G, then T and/or O.

The total voltage drop from test points D to the load test points should be 5% or less. Use the following formula to determine the percentage of voltage drop:

$$\frac{\text{Voltage at test points D} - \text{Voltage at load test points}}{\text{Voltage at test points D}} \times 100$$

For example, if the voltage at test points D is 27 volts and at the load test points is 24, the percentage of voltage drop is:

$$\frac{27 - 24}{27} \times 100 = \frac{3}{27} \times 100 = .111 \times 100 = 11.1\%$$

If the percentage of total voltage drop is higher than 5%, go back through test points D, G, N, then R and/or T to find the section of the system with unacceptably high voltage drops.

> NOTE
>
> The blocking diode, if used, normally has a voltage drop of 0.5 to 1.0 volts at test points H. A higher voltage drop indicates a defective diode. Testing the diode is described in Section 4.3.4.

4.3.2 Loads. Determine the power consumption of the loads and the amount of power available from the photovoltaic system. If the loads are too large, or operate too many hours per day, the system will constantly be at a low state of charge, the loads will not operate properly, and eventually battery damage will occur.

Measure the current draw of every load during operation. Ignore starting surges. Multiply the operating current, in amps, times the load's nominal voltage to determine the power consumption in watts.

The power consumption of the loads can sometimes be approximated by reading nameplate wattage ratings. If nameplate ratings are in amps, multiply each load's nameplate amps rating times its nominal voltage to determine rated watts.

The system's available power rating will vary with the amount of sunlight that is available. The design authority should have an estimate of available power that was made during the design of the system.

If the total power consumption of the loads is less than or equal to the estimated power available from the system, but they are still using more power than the system can supply, the load size must be reduced or the photovoltaic system size increased.

Another likely reason for improperly operating loads is broken or turned off loads. Check the loads for turned off switches, blown fuses, and tripped thermal circuit breakers. Make sure line cords are plugged in.

Disconnect the load. Use an ohmmeter to check the load for short circuits, open circuits, and ground faults.

Although it should already have been checked, excessive voltage drops will cause improper load operation. Check for this at test points D, G, and N, and at the load test points.

Finally, make sure the polarity of the photovoltaic system is the same as that of the loads.

4.3.3 Batteries. Measure the battery bank total voltage with a DC voltmeter on test points L+ and L-. Measuring the specific gravity of the electrolyte is the most desirable method to determine state of charge, but for troubleshooting, accurate measurements of voltage are acceptable.

Low battery voltage

Low battery voltage is usually caused by loads which are oversized or running too long; charge controller failure; switch, fuse, or wiring problems; or long periods of cloudy weather.

If not already done, check loads, switches, fuses, and wiring as described in Sections 4.3.1 and 4.3.2. Check the charge controller as described in Section 3.1.6.

Check the electrolyte level of every cell in every battery. They should all be near the same level. The electrolyte should be reasonably clear.

If the battery bank is too large for the array, undercharging can result. Check with the design authority to be sure the two are properly matched.

Charging at a very high rate can reduce battery capacity. For most lead acid batteries, the charging current should be between C/10 and C/20 (one-tenth to one-twentieth of the total battery capacity).

Also check if the voltage window of the batteries and the array are compatible. The voltage from the photovoltaic array at peak power must be higher than the battery bank voltage for charging to occur.

Turn off the array disconnect switch, or disconnect the array from the array terminals on the charge controller. Check the available array voltage at test points D.

If the open circuit array voltage is not at least five volts higher than the battery voltage when the batteries are at a low state of charge, the array is mismatched to the batteries, or there is something wrong with the array. As an example, in a 12 volt system, the open circuit voltage of the array should be around 18 to 20 volts. The battery open circuit voltage should be around 11 to 14.5 volts.

Make sure the system performance is not being reduced by shaded or dirty modules, or inadequate sunlight. If the loads are using more power than the system design capacity, the load size must be reduced or the system size increased.

Open the battery disconnect switch or disconnect wiring at test points L. Measure the voltage of every battery in the array at test points I, as described in Section 3.1.7. Record the results as the measurements are made on a copy of the Inspection Worksheet from the end of Chapter 3.

If the connections between individual battery cells are external, measure and record the voltage of individual cells on the same worksheet.

Any battery or cell with a voltage 90% or less of the average voltage of the entire battery bank is probably defective and should be replaced.

Make sure that all series and parallel strings of batteries have equal numbers of batteries and cells. If not, uneven charging will result.

If no cause can be found for the batteries' low voltage, the batteries may be damaged or an inappropriate type, and are not able to accept a charge.

<u>Batteries not able to accept a charge</u>

Batteries that cannot accept a charge have been harmed by overcharging with subsequent water loss, being left at a low state of charge for long periods, or physical damage.

The state of charge of batteries in this condition can be high, low, or normal. The batteries will rapidly accept a charge, and will rapidly discharge. The battery bank acts as if most of the parallel strings have been removed.

Check loads, switches, fuses, and wiring as described in Sections 4.3.1 and 4.3.2 to find causes of discharging. Check the charge controller as described in Section 3.1.6 for causes of over- or undercharging.

If the batteries have been damaged by repeatedly being discharged too deeply, make sure there is a charge controller, which has a low voltage disconnect feature, and that it is working properly. Check the position and operation of the temperature compensation probe, if used. Dispose of damaged batteries in accordance with local standards and procedures. The inverter low input voltage shut down feature, if provided, should be checked.

If the batteries have been damaged by overcharging, check the high voltage termination setting of the charge controller, and the position and operation of the temperature compensation probe, if used.

Be sure to check the electrolyte level in all cells in all batteries.

High Battery Voltage

The usual reason for overcharging batteries is a faulty or misadjusted charge controller. Use the procedures in Section 3.1.6 to check the charge controller. Make sure the temperature compensation probe, if used, is securely connected and in good thermal contact with the side of one or more batteries.

If the battery bank is too small for the array, overcharging can result. Check with the design authority to be sure the two are properly matched. Check the charging rate as well, as battery capacity is maximized by a charging rate between C/10 and C/20 (See Section 2.5.1).

Also check if the voltage window of the batteries and the array are compatible. In a self-regulating system, modules with too high an output voltage will overcharge the batteries.

4.3.4 Charge Controllers. Many charge controller problems are caused by loose connections, blown fuses, or switches in the wrong position. Look for evidence of temperature extremes or high humidity in the area where the charge controller is installed.

If possible, remove the charge controller cover and look for dirt, corrosion, insects, or other problems at the relay contacts.

Keep in mind that many charge controller problems result from oversized loads or starting surges from loads. These range from blown fuses to low battery voltages and improperly operating loads. Measure the current draw of the loads, both operating and starting, and compare it to the design load and the charge controller nameplate amperage rating.

Compare the readings of any charge controller meters to those measured by portable meters. Use these measurements to confirm that LEDs and other indicators are "telling the truth."

Typically, the accuracy of high quality portable meters is higher than those used on the system. It may be possible to recalibrate the system meters to agree with the portable meters.

Make sure the voltage windows of the charge controller and the batteries are compatible. Confirm that the inverter, if used, is wired directly to the batteries, and not to the charge controller.

After checking all these, perform the troubleshooting procedures which follow. These tests must be performed on a sunny day.

> NOTE
>
> If a portable power supply is available, perform the optional performance tests described in Section 3.1.6, instead of these tests.

> CAUTION!
>
> Always observe the manufacturer's connect/disconnect sequence when working on charge controllers. Failure to do so may result in damage to the unit. Also remember to obtain permission to disconnect critical loads.

<u>High Voltage Cutoff</u>

Disconnect the loads and allow the system to charge the batteries up to the charge termination setting. Occasionally check the battery voltage at test points L during the charging process.

If the charge controller has a float or pulse charging feature, observe the current flow from the array as the battery voltage approaches the charging termination setting.

If the unit has a charging indicator, make sure it goes off when the voltage increases to the charging termination setting.

If the float charging feature is working, the current flow will drop down to a few hundred milliamps. If the pulse charging feature is working, the current flow will start and stop in cycles of a few minutes. In some systems the pulses may be so fast that they cannot be seen on a meter.

Make sure the temperature compensation probe, if used, is in secure thermal contact with the side of one battery. Check the "battery sense" terminals of the charge controller for clean, secure connections.

Charging Resumption Setting

Place a snap around (clamp-on) DC ammeter on the wire at test point M. Disconnect the array and turn on all the loads, while watching the ammeter for the starting surge of the load.

Monitor the voltage at test points L until the voltage drops back below the charging resumption setting.

At this point, note if the charging LED comes back on. Reconnect the array for a moment, and use the DC snap-around ammeter to confirm that current is once again flowing from the array to the batteries.

Adjustable Settings

If any of the settings can be readjusted, turn the adjustment knob until the unit connects at the correct voltage. This voltage is the one read by the portable meter at test points L. Normally, the placement of numbers on the adjustment dial is less accurate than the portable meter reading.

If the charge controller does not have adjustable settings, and it is out of adjustment, it must be replaced. Follow the manufacturer's standard return procedures for repair or replacement if the unit is still under warranty.

Blocking Diode

If the system includes a blocking diode as part of the charge controller, or as a separate component, test it. If the controller is a series-relay type, the system may not require a blocking diode. Consult the manufacturer's information to determine which type of charge controller is in the system.

With the array charging the batteries or supplying power to the loads, measure the voltage at test points H. The positive is on the array side of the blocking diode.

If the diode is inside a charge controller and cannot be reached, use test points G+ and L+, when the array is charging the batteries. If the array is powering the loads, use test points G+ and O+ and/or T+.

A reading of 0.5 to 1.0 volts indicates the diode is operating properly. A higher reading indicates a defective diode which must be replaced.

If the diode is part of a charge controller, the controller must be repaired or replaced. Follow the manufacturer's standard return procedures for repair or replacement if the unit is still under warranty.

Other Charge Controller Concerns

If the charge controller does not operate properly, try disconnecting it completely from the system, waiting at least 10 seconds, and reconnecting it. It may just be out of synchronization. The unit would normally reset itself at the next sunrise, but disconnecting and reconnecting has the same result for some controllers. (Others may require 24 hours of operation to reset themselves.)

If the relays on the charge controller are "chattering," make sure the inverter, if used, is connected to the batteries and not to the charge controller. Also, if the battery voltage at test points L is low, there may not be enough voltage to operate the charge controller's relay coils properly.

4.3.5 Inverters. Measure the operating and starting surge current flow of the AC loads connected to the inverter. Use an AC snap around ammeter on the wire at test point R+.

Compare the actual current flows to the inverter's rated capacity for operation and surge current. If the load currents are too high, the load must be reduced or the inverter replaced with one with a larger capacity.

Check the inverter operation at the time of service. LEDs should indicate actual operating conditions. Compare inverter meters to the readings of portable meters. A buzz or hum is normal, as is a few seconds of delay on units which turn themselves off or to idle when there is no AC load.

Turn on an AC load and confirm that the inverter either starts immediately or starts after a few seconds of delay. If the inverter does not start, check if it has a low voltage disconnect and if it is open due to low battery voltage.

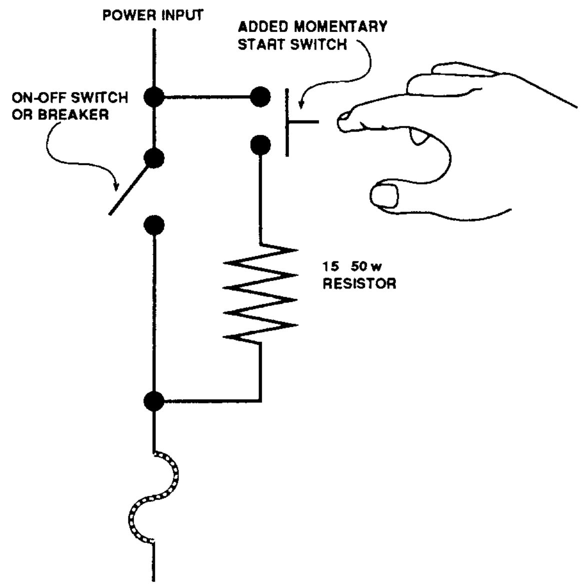
If the battery voltage is high, many inverters will not turn on until the voltage has dropped below levels harmful to the inverter. In this case, connect a load to the batteries directly, while measuring the total battery bank voltage at test points L.

When the voltage has dropped below the operation resumption setting of the inverter, it should come on.

In some cases with manual start inverters, the current flow required to charge up the unit's capacitors may blow its DC fuse or circuit breaker the first time the unit is used.

If this occurs, wire a 15 ohm, 50 watt resistor in series with a momentary contact switch. Connect this resistor/switch circuit in parallel with the start switch or circuit breaker, as shown in Figure 4-2. This will bypass the circuit breaker whenever the switch is depressed, but the resistor will limit the current flow.

FIGURE 4-2
Momentary Contact
Switch and Resistor
to Start Inverter



To start the inverter, depress the switch for a few seconds to charge up the capacitors before turning on the regular start switch.

Note that this problem does not occur on inverters which idle between operating cycles, since there is always some current flow to keep the capacitors charged.

4.3.6 Arrays Before testing the array, confirm that there are no short circuits or ground faults in the system, as described in Section 3.1.6 in the Inspection chapter. Then follow the information in the same section to measure the array and modules' open circuit voltage and short circuit current.

All frames, controller chassis, conduit, junction boxes, and other metal components must be electrically tied together and to an earth ground rod driven firmly into the ground. Use an ohmmeter to confirm electrical continuity through the entire grounding system.

Remember that the negative wiring of DC-only systems should also be tied to the earth ground. On systems with AC-only, or AC and DC, the negative lines should "float," with no connection to earth ground.

Open circuit voltage

Compare the measured amount of open circuit voltage from the array against the manufacturer's specifications. Remember to multiply the manufacturer's specified voltage times the number of modules in series in the array.

Record each module's voltage on the worksheet at the end of this chapter. Compare the measured open circuit voltage for the modules against the manufacturer's specifications. If any module is 10% or more below the average voltage, also note it on the worksheet.

WARNING!

When measuring the short circuit current of either the modules or the entire array, be careful not to also short circuit the battery bank. An explosion can result. Open a disconnect switch between the short circuit and the batteries first. Also, the wire used to short circuit the array can be very hot.

Short circuit current

Use a short piece of wire to connect the positive and negative terminals of each module, as shown in Figure 3-12 in the Inspection chapter. Use the information in Appendix C to determine the appropriate gauge of wire for the anticipated current.

Use a snap around DC ammeter to make the actual measurements. Record the results on the worksheet at the end of Chapter 3.

Use a solar energy meter to determine how much sunlight is available, as shown in Figure 3-13 in the Inspection chapter. Compare the measured amount of current from each module against the manufacturer's specifications for that amount of sunlight.

Record each modules' short circuit current on the worksheet. If the current from any module is 10% or more lower than that from the others, record that as well.

Reconnect the connections in the array, and short circuit the positive and negative leads of the entire array. Again, use the information in Appendix C to determine an appropriate wire gauge.

Use a snap-around DC ammeter again to make the actual measurements, as shown in Figure 3-10, in the Inspection chapter. Record the results on the worksheet at the end of Chapter 3.

CAUTION

The amount of current from the entire array may be much higher than the capacity of a typical DC ammeter. Use the manufacturer's data to make an estimate of the maximum current before making the measurement. Multiply the current per module times the number of modules in parallel in the array. Start with the highest DC amps scale on the meter, and work down. If the inverter is too small, divide the array into sections

Use a solar energy meter to determine how much sunlight is available. Compare the measured amount of current from the module against the manufacturer's specifications for that amount of sunlight.

Remember to multiply the manufacturer's specified current times the number of modules in parallel in the array.

Dirty, shaded, or damaged array

The modules' glass covers should be unbroken and reasonably clean. All modules should be unshaded throughout the day. "Spot" shading of a few cells or modules in the entire array must be eliminated, since the array output is drastically reduced and affected modules may be damaged.

Conduit and connections must all be tight and undamaged. Look for loose, broken, corroded, vandalized, and otherwise damaged components. Check close to the ground for animal damage.

If conduit was not used, check cable insulation carefully.

Remove covers to check wiring and wiring connections for similar damage or degradation. Also look for burnt wiring or terminals. If plastic conduit is used, check for a continuous earth ground wire throughout the system.

Array tilt and orientation

As discussed in Section 2.3.5, the array tilt and orientation should be appropriate for the application. Refer to this section in the Operation chapter to confirm that the array is correctly aligned.

Blocking and isolation diodes

If the array includes blocking or isolation diodes, measure the voltage drop across each diode when current is flowing from the array to the batteries. The positive side of the diode should be on the array side.

If the measured voltage drop is between 0.5 and 1.0 volts, the diode is operating correctly. If the voltage drop is higher, the diode is defective and must be replaced.

Bypass diodes

Bypass diodes may be tested by shading the module under test and then checking, with a clamp-on amp meter, to see if current is flowing through from the rest of the array. Replace the diode if there is little or no current flowing.

4.4 TROUBLESHOOTING RECORDS

Use a copy, or modification, of the sample inspection record sheet (from the previous chapter) to record the results of troubleshooting a photovoltaic system. If detailed investigations of battery state of charge or module outputs are made, the inspection checklist includes places to record this information. As with inspection, keeping a service log creates a history of the system. Those working on the system in the future will benefit from this information.

The same type of historical perspective can be used by future inspectors and troubleshooters to detect patterns of gradual performance decline. Keep all the system documentation in one place. This can be at the system site, but a better place to store it is in the maintenance shop, bringing it to the site when service is done.

Knowing the system's history can simplify troubleshooting, and make it possible to combine troubleshooting and repairs on one trip.

4.5 QUESTIONS FOR SELF-STUDY

Directions: Choose the best answer to each question.

1) When do photovoltaic modules produce electricity?

   A) Only in direct sunlight
   B) Only when connected to a battery bank
   C) Only when connected to a load
   D) Whenever light shines on them

2) Lead acid batteries contain which of the following?

   A) Oil
   B) Caustic soda
   C) Baking soda
   D) Sulfuric acid

3) Oversize loads will cause which of the following?

   A) Damaged photovoltaic modules
   B) Damaged charge controllers
   C) Damaged batteries
   D) Excessive battery water loss

4) A faulty blocking diode will cause which of the following?

   A) Overcharged batteries
   B) Battery discharge at night
   C) Overheated photovoltaic modules
   D) Poor charge controller temperature compensation

5) Muddy electrolyte in a battery indicates which of the following?

   A) Age
   B) Overcharging
   C) High temperatures
   D) Freezing

6) After an AC load is turned on, an inverter does not supply power for a few seconds. Which of the following is the problem?

A) Oversize loads
B) Array voltage is too low for the load
C) Battery voltage is too high for the load
D) Nothing is wrong

7) Which of the following is in the ideal charging rate range for lead acid batteries?

A) C/5
B) C/15
C) C/25
D) C/35

8) Which of the following is the usual reason for overcharged batteries?

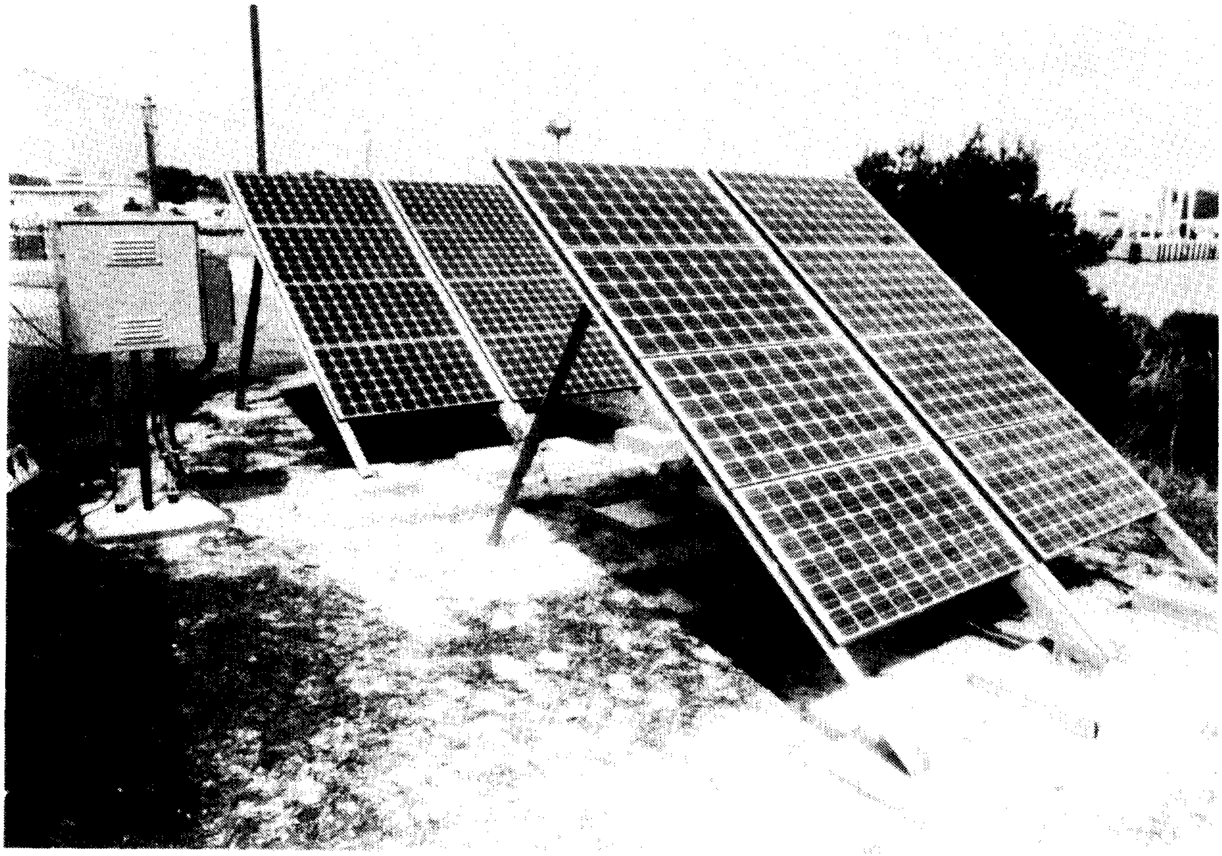
A) An undersized load
B) An oversized array
C) More sunlight than estimated
D) A faulty charge controller

9) Sulphation is caused by which of the following?

A) Undersized wiring
B) Inadequate inverter capacity
C) Undercharging
D) Not enough sulfuric acid in the electrolyte

10) Loose, broken, or corroded connections will cause which of the following?

A) Voltage drop
B) Excessive battery gassing
C) High photovoltaic module temperatures
D) More blown fuses



Cathodic Protection of a Seawall
Naval Coastal System Center
Panama City, Florida

5.0
REPAIR

What You Will Find In This Chapter

This chapter contains information on repairing a photovoltaic system. It is assumed you understand basic electrical concepts, particularly those of photovoltaic systems. It is also assumed you can use an electrical meter to measure voltage, current, and resistance.

Information on normal system operation can be found in Chapter 2, Operation. Troubleshooting information is described in Chapters 3 and 4.

Appendix A lists the tools and materials you will need to perform repairs.

5.1 REPAIR AND REPLACEMENT

5.1.1 Permission to Disconnect Critical Loads. Many photovoltaic systems power critical loads, such as communication systems, warning lights, and others. Be sure to get permission from the proper authority to disconnect such loads before doing so. In some cases, an auxiliary power supply may be necessary to operate the load while repairing the photovoltaic system.

WARNING!

Be sure to open disconnect switches during any repair operation involving wiring. When working on the wiring of photovoltaic arrays, cover the modules with an opaque material, turn them face down on a clean, soft surface, or work at night.

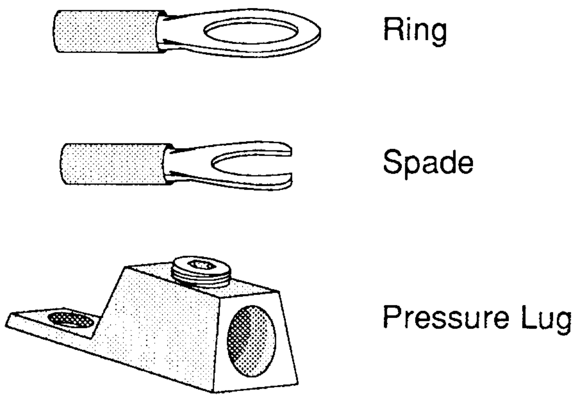
5.1.2 Wiring. Before making repairs to system wiring, confirm that all switches are in the correct position, fuses or circuit breakers are not blown or tripped, and the loads are not greater than those in the original design.

Connections

System repairs are most likely to involve the interconnections between modules and other components. Pull on all crimp terminals to see if the connection is tight. Loose connections must be tightened. Corroded terminals and wiring should be replaced. If this is not possible, and there is no serious damage, they can be cleaned up, reconnected, and protected from further corrosion.

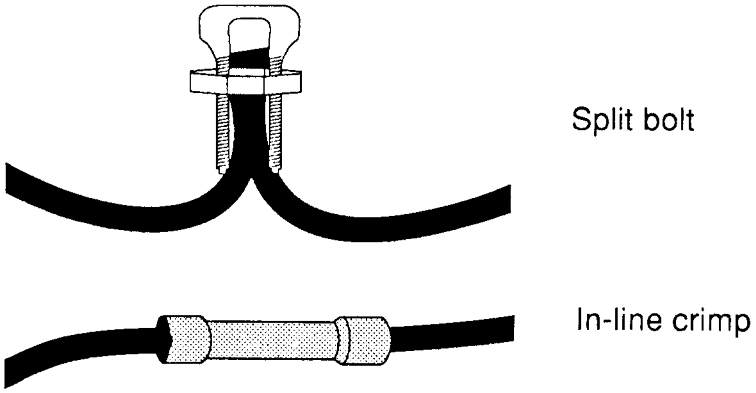
Wire to screw type terminal connections should be remade using ring terminals, unless frequent disconnection is probable. In this case, spade terminals can be used. Pressure lug terminals do not require a terminal on the end of the wire. Figure 5-1 shows a variety of wire to terminal connections.

FIGURE 5-1
Wire to Terminal
Connectors



Wire to wire connections can be made with crimp-type connectors or wire nuts. In either case, be sure to use the appropriate size connector. This information is usually furnished on the connector box. Figure 5-2 shows both types of connectors. Wire nuts are not recommended for low voltage, high current DC systems, e.g., < 50 volts.

FIGURE 5-2
Wire to Wire
Connectors



Most photovoltaic system wiring is copper, but aluminum can be used for long runs. Aluminum-to-copper connections must be made with "AL" type connectors.

Crimp-type connectors must be correctly installed with a crimping tool, not pliers. Remember that this type of connector is designed for use with multi-strand wire only.

All wire to wire connections must be made in an appropriate junction box or equipment enclosure. Cable or conduit connections must furnish strain relief. Connections to outdoor junction boxes must be made only in the bottom, and should include drip loops (Figure 5-3).

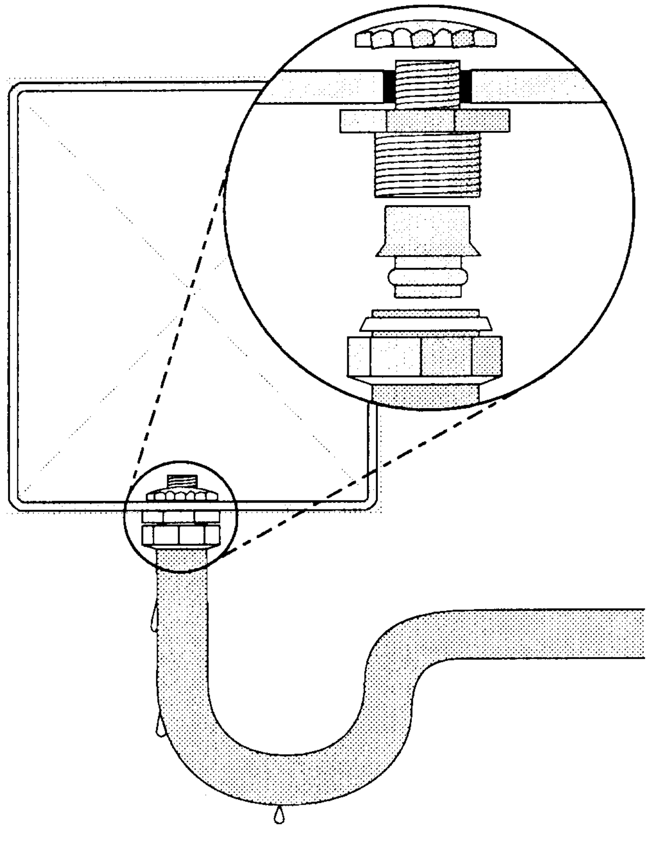


FIGURE 5-3
Connections to
Outdoor Junction
Boxes

The gauge and length of wire should be checked, and wire of inadequate gauge must be replaced. This is particularly important in the high amperage, low voltage DC wiring typical of photovoltaic systems.

Generally, the total voltage drop from the service entrance to the load should be no higher than 5%. The voltage drop of branch circuits should be no more than 2%. Tables C-2 to C-8 in Appendix C give the appropriate wire gauge for different wire run lengths.

Color coding

Correct wire insulation color coding is critical for your safety, and that of others working on the system. Remember, the DC positive line may be red, and the negative may be black. But if either conductor is grounded, the NEC code requires that is must be white. This is the same as in AC systems. If metallic conduit does not supply grounding, the grounding wire is green or bare.

As usual, the hot AC wire is black, the grounded conductor (common) is white, and the grounding wire (equipment grounding wire) is green or bare.

Fuses, circuit breakers, and switches

Replacement fuses, circuit breakers, and switches must have adequate capacity for the current load. Circuit breakers, fuses, and switches must be rated for use with DC current. "AC/DC" rated switches are rated for DC applications.

AC rated circuit breakers and switches will be damaged by the arcing of DC current across the contacts as they open and close. If a DC rated circuit breaker is not available, a DC rated fuse should be used instead.

Table C-1 in Appendix C lists the maximum number of amps for various sizes and types of wires, and can also be used to determine the correct size of fuse or circuit breaker.

Glass, plug, or cartridge fuses must not be used, unless they have a UL DC rating. Time delay ("slow-blow") fuses should only be used for high in-rush current loads such as motors or inverters. These are the only applications requiring the time delay feature.

Do not replace a blown fuse, or reset a tripped circuit breaker without determining what caused the over-current situation.

Other wiring repairs

Replace any damaged conduit or junction boxes. Conduit must be properly supported to prevent sagging or other damage.

Be sure to reconnect all grounding connections. Even if no repairs must be made to the grounding system, check it carefully for loose connections and broken or corroded components. Check for continuity after making repairs.

5.1.3 Modules. Module failures are almost always caused by vandalism or environmental extremes. But remember that low output can also be caused by dirt shading the module. Before replacing damaged modules, try to determine what happened and take measures to protect the systems against a reoccurrence.

If vandalism or animal damage is suspected, and a fence is proposed, remember the significant degradation of performance and possible module damage caused by array shading. The most common source of point shading on arrays is fence posts.

When replacing a module which is part of a series string, use one with an integral bypass diode, or include a diode in the array connections between modules.

If an identical match for the damaged module cannot be found, match the open circuit voltage to insure proper system operation. This is particularly important in systems with less than ten modules. The rated current output is less important than the voltage.

If an array diode must be replaced, its voltage and current ratings must be higher than the maximums the array or array section can create.

Remember that a blocking diode is not used if the charge controller opens the circuit at night or during cloudy weather. (Refer to Section 2.5.2)

5.1.4 Mounting Systems. Repair mounting systems with materials compatible with the module frames, the anchor bolts or other hold-down devices, and the remainder of the mounting system. Avoid the use of galvanized steel, particularly around aluminum module frames or racks.

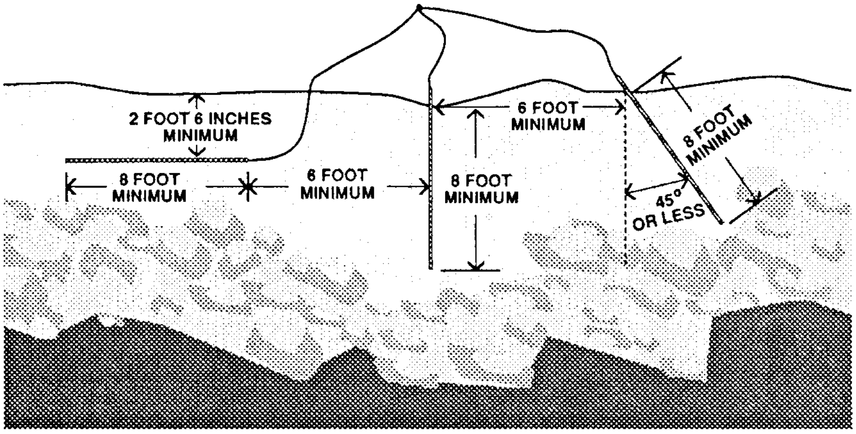
If uncoated steel members must be used, protect them from corrosion with paint. Exposed parts of steel fasteners can be protected with a thin coat of silicone sealant, which can be removed for future tightening.

Remember that in most situations, the wind loading on an array is greatest in an upward direction. Mounting uprights and fasteners should be designed and sized accordingly.

5.1.5 Grounding Systems. Complete and adequate grounding must be a part of every photovoltaic system, for the protection of people in contact with it and the system itself. Prior to making any repair to a photovoltaic system, check the grounding of the equipment and the grounding wire or conduit.

Tighten all connections, and replace or repair any damaged connections and wire. If grounding electrodes (rods) appear corroded, leave them in place and connected, and add and connect others as needed. Install rods at least six feet from each other to improve their grounding efficiency and follow the requirements of the NEC code.

FIGURE 5-4
Grounding
Electrodes



New grounding rods must be driven at least eight feet straight down into the earth. If a rock layer does not allow this, they can be driven in at angles of up to 45 degrees. If even this is not possible, eight foot rods can be buried in a trench at least two and one-half feet deep (Figure 5-4).

If the top of the rod is exposed, it must be protected from physical damage. Iron or steel rods must be at least 5/8 in. in diameter. Nonferrous rods (usually copper) must be at least 1/2 in. in diameter.

Bond all the rods together using an appropriate size wire. The gauge of the bonding conductor must be at least as large as the largest of the following:

- the largest conductor in the system,
- the neutral conductor in a three-wire system,
- AWG #8, if copper, or
- AWG #6, if aluminum.

The grounding electrodes should be bonded to the photovoltaic system between the point where all the parallel module strings join together and the rest of the system (Figure 5-5). This corresponds to a point between test points D- and G- (Figure 4-1).

Locating this connection as close as possible to the photovoltaic array provides better protection of the system against voltage surges caused by lightning.

The above conductor size requirements must also be used for the connection from the ground rod(s) to the system grounded conductor.

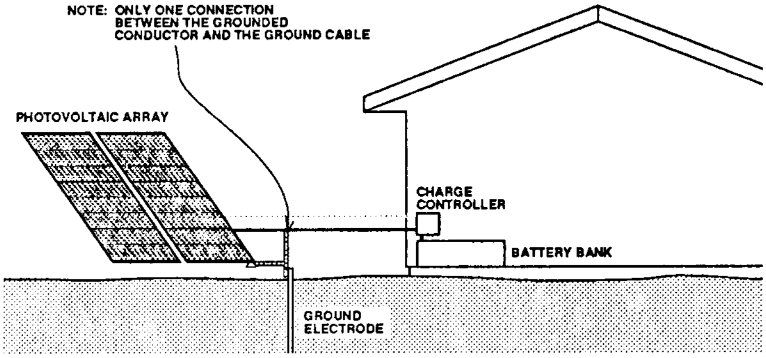


FIGURE 5-5
Point of System Grounding Connection

In a two-wire (one positive, one negative, and an equipment ground) DC photovoltaic system, connect the grounding electrodes to the negative conductor and the grounding system of conduit, boxes, and grounding wires (Figure 5-6).

NOTE
Two-wire systems actually use three conductors.

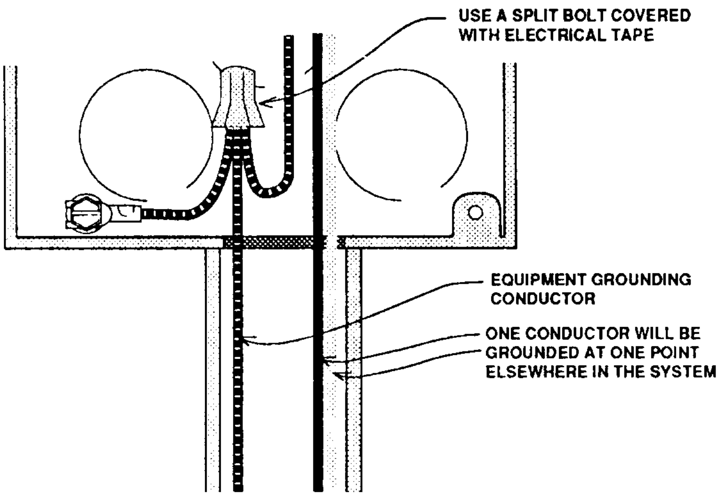


FIGURE 5-6
Grounding Connections in a Two-Wire Photovoltaic System

In a three-wire (one positive, one negative, one grounding) DC photovoltaic system, connect the grounding electrodes to the grounding wire (Figure 5-7).

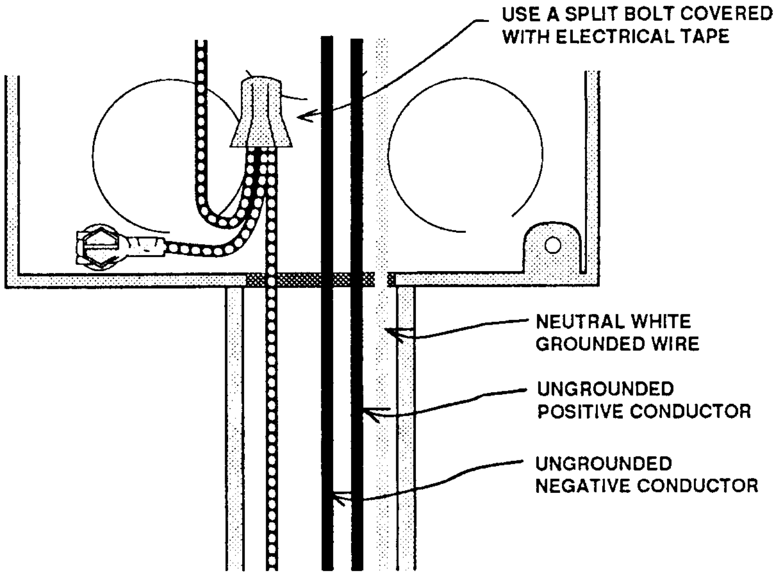


FIGURE 5-7
Grounding Connections in a Three-Wire Photovoltaic System

If metallic conduit is being used for equipment grounding, tighten any loose conduit connections. Use an ohmmeter to confirm that the conduit, boxes, and other exposed metal surfaces of the system are bonded to each other and the grounding electrodes.

5.1.6 Batteries. This section begins with general information on batteries, followed by material specific to lead acid batteries.

WARNING!

Even at the low voltages typically used, photovoltaic battery banks contain lethal amounts of current! Lead acid batteries are filled with high concentration sulfuric acid and give off explosive hydrogen gas while charging. Always wear proper eye and skin protection, have baking soda, plenty of fresh water, and an adequate first aid kit available, and do not smoke or use fire or spark sources near batteries of any kind.

FIRST AID INFORMATION

If battery acid should get in your eyes, flush them with water for at least ten minutes and seek immediate medical attention. If acid splashes on your skin, neutralize it immediately with a water and baking soda solution, and flush with plenty of fresh water. If acid is taken internally, drink large quantities of water or milk, follow with milk of magnesia, beaten egg, or vegetable oil, and seek immediate medical attention.

When making any battery repair, follow the procedures in Section 6.1.7 in Chapter 6 for tightening and cleaning connections and adding water.

To remove the connections when replacing batteries, use a terminal puller, if one is available. After removing the connector, use a cable clamp spreader (Figure 5-8) to expand the clamps. Remove the negative terminal connector first.

When replacing damaged batteries, use a battery carrier if possible (Figure 5-9). Always carry batteries by the side walls, as pictured, rather than the end walls. Clean up any spilled electrolyte immediately by sprinkling baking soda on the spill, flushing with water, and mopping up with rags.

FIGURE 5-8
Battery Clamp
Spreader

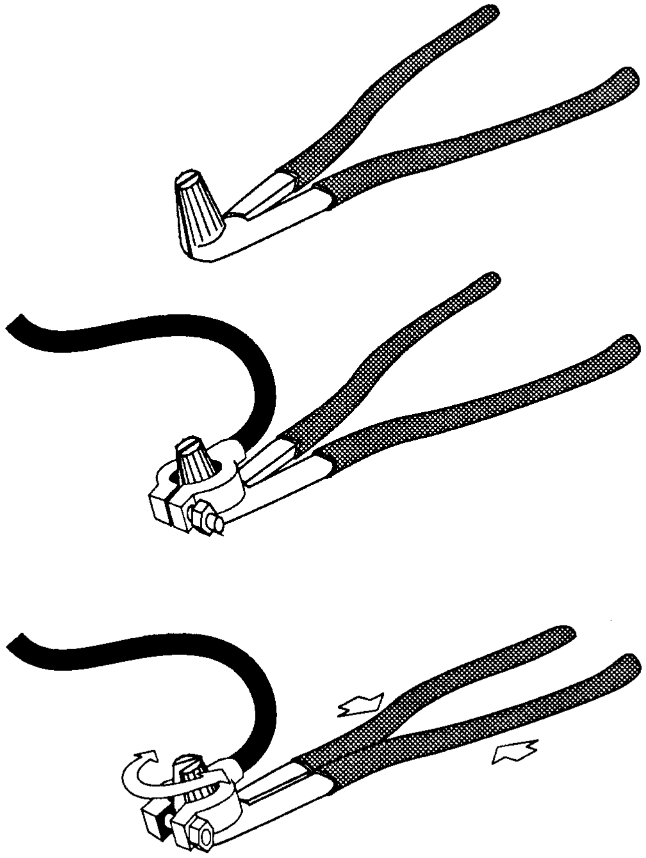
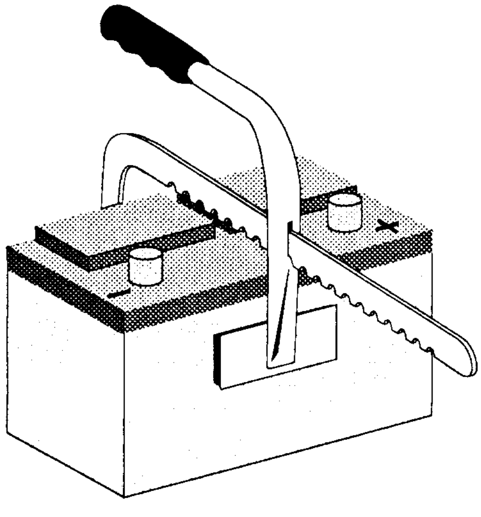


FIGURE 5-9
Battery Carrier



Avoid contact with the leads from adjacent batteries during replacement. Connect the positive terminal first. Be sure the batteries are secured in a stable position and reconnect tie-downs, if used.

WARNING!

When making connections on or around batteries, avoid making sparks during the last connection. This is particularly important if the batteries have recently been generating hydrogen gas during charging. Open a disconnect switch to prevent current flow until the final connection is made. See Figure 2-3, page 9.

Wiring used on batteries can be type THHN building wire, 600 volt UL listed welding cable, or UL listed battery cable. Batteries should be located in an insulated enclosure, such as a plywood box.

WARNING!

If a switch, charge controller, or inverter is in the battery enclosure, move it to another location.

Confirm that a No Smoking sign is posted and that adequate ventilation exists. If an active venting system with a fan is used, make sure it is working properly.

If the battery cells do not have flame arrestor caps, consider changing them, if possible. Another upgrade is to install recombination caps to reduce water requirements.

When transporting batteries, be sure they are tied down to prevent them from falling over. Dispose of damaged batteries in accordance with local standards and procedures. Do not throw them into trash bins or dumpsters.

Lead acid batteries

If it is necessary to prepare electrolyte (acid), always pour the acid slowly into the water, not the water into the acid. Heat is generated during mixing, so proceed slowly, stir as the acid is added, and stop if noticeable heat builds up. Use only plastic or lead-lined containers, funnels, and stirring tools.

Hydrometer readings made right after adding electrolyte will not be accurate. The contents of the cell must be mixed, by charging, before measurements of specific gravity can be made. Remember to compensate for temperature. Further information on measuring specific gravity is in Section 3.1.7.

After a battery has been replaced, the entire bank should be given an equalization charge with the array or another power source. The process is described in Section 6.1.7.

5.1.7 Charge Controllers.

> CAUTION!
>
> When disconnecting or rewiring charge controllers, be sure to follow the manufacturer's recommended sequence for disconnection and reconnection. Failure to follow these procedures exactly will result in damage to many models.

Replacing or adding a charge controller

Charge controllers must be installed in a dry location which is out of direct sunlight. During normal phases of operation, shunt-type controllers build up a significant amount of heat, which must be removed by adequate ventilation.

> **WARNING**
>
> Charge controllers must never be installed in the same enclosure as batteries. Not only is a battery box a corrosive environment, but the hydrogen gas given off by the batteries can be ignited by the arcs created by a controller's contacts.

Wiring

Wire or cable used near a charge controller can be of a type rated for dry, indoor locations, as the controller must be installed in such an environment.

Conductors must be sized appropriately. Since the charge controller is subjected to the full output of the array, the conductors attached to it must be rated for the total short circuit current of the array.

This is somewhat higher than the operating current, and is determined by multiplying the short circuit current of one module times the largest number of modules connected in parallel.

Sometimes, two charge controllers are installed in parallel. This can reduce the required conductor size, to each controller, as the array's current output is reduced. However, the ampacity of the conductors coming from the array before splitting off to the individual controllers is still the original higher quantity (Figure 5-10).

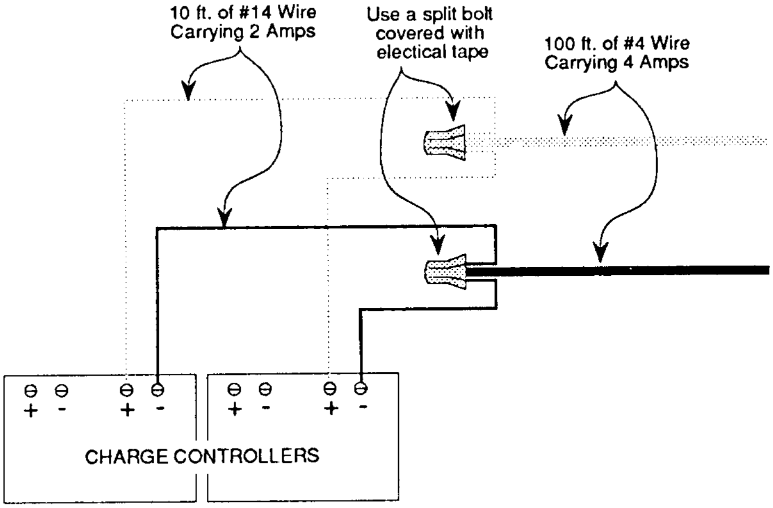


FIGURE 5-10
Current Flows and Wire Sizes in a System with Two Parallel Charge Controllers

In low voltage systems (less than 50 volts), a wire size of #12 AWG or larger must be used.

If multistrand wire is used, be very careful to prevent strands of wire at one terminal from contacting other wires or terminals. Tinning with electrical solder is one way to prevent this.

A better way to make terminal connections is with crimp-on terminals. Use ring, rather than spade, terminals unless the terminal must be disconnected more than twice a year. Use the correct size jaws on a crimping tool to crimp on the connectors. Do not use a pair of pliers.

WARNING!

Open the disconnect switches from the array and the battery bank before making or breaking connections at the charge controller. Potentially lethal amounts of current and voltage may be present in these wires.

Maintain correct wire insulation colors: white for the grounded conductor (usually negative), and bare or green if an equipment grounding wire is used instead of metallic conduit. Red is normally a good choice for the positive conductor unless it is grounded. In that case, it must be white. If the correct insulation color is not available, use appropriately colored tape to code the wiring.

Temperature compensation probe

If a replacement charge controller includes a temperature compensation probe, or the probe is replaced on an existing controller, secure the probe halfway up the side of a battery.

Carve a hollow out of a piece of rigid foam insulation the same size as the probe, with a channel out of the hollow for the probe wire. Tuck the probe in the hollow, and tape the insulation to the side of the battery. Wrap the tape all the way around the battery for a better grip. (Figure 5-11)

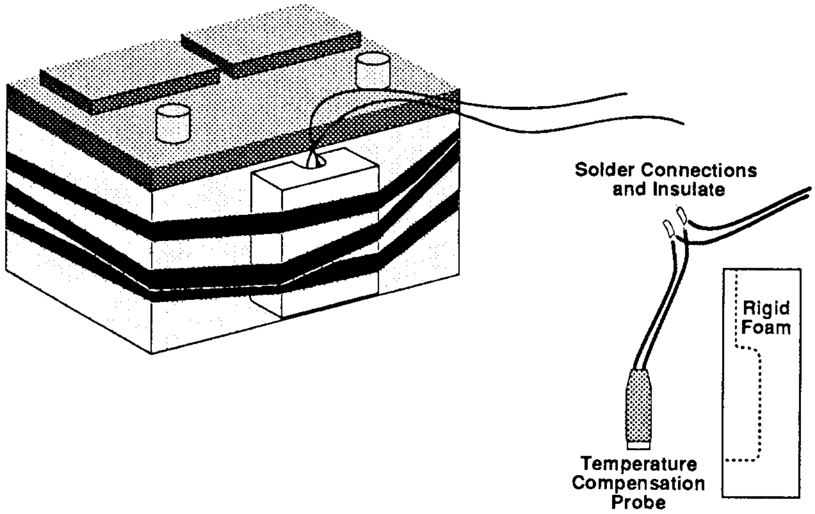


FIGURE 5-11
Temperature Compensation Probe Installation

Install the probe in a location sheltered from cold air and direct sunlight. If the probe comes with short wires, or the probe wiring must be extended, the connections <u>must</u> be soldered.

If a replacement probe is not available, many controllers can be operated with a jumper wire or a specific resistor until a new probe can be obtained. Consult the manufacturer's information for details.

Adjustments

Adjustment is normally needed only if the battery bank is consistently being overcharged, or allowed to discharge too low. Therefore, most charge controllers, particularly small ones, are not adjustable.

When a system has a non-adjustable charge controller with inappropriate settings, consider installing a different one, with charge termination and resumption settings more appropriate for the battery type and loads used in the system.

If the charge controller is adjustable, as shown in Figure 5-12, the characteristics of the batteries must be known before making any adjustments. If the battery manufacturer's information is not available and it is a lead acid battery, use Table 2-3 and/or Figures 2-49 and 2-50 in Chapter 2, Operation, to determine the upper and lower limits of state of charge for the type of battery in the system.

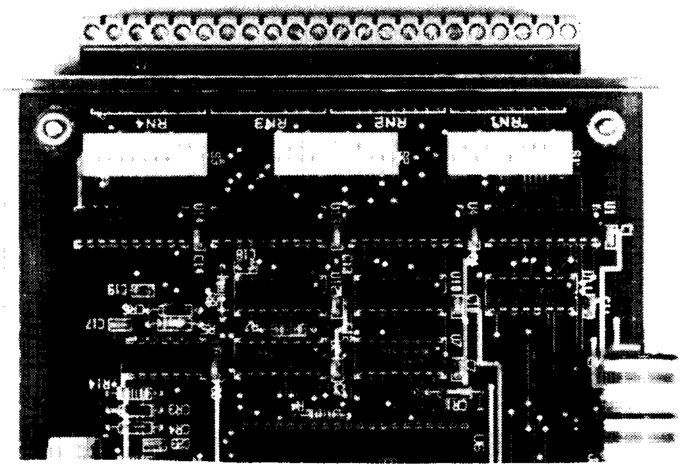


FIGURE 5-12
Charge Controller
Adjustment Dip
Switches at Bottom of
Unit

Photo Courtesy of Integrated Power Corp.

Check the battery voltage or specific gravity over the next few days after adjustment, to confirm that the controller is effectively protecting the batteries from excessive charging and discharging. If this inspection is not practical, use a portable adjustable power supply as described in Section 3.1.6 for accurate adjustment of the controller.

<u>Synchronization of charge controllers</u>

Some controllers, such as series-relay types, may operate incorrectly when they are first energized. Their internal timers are out of synchronization. Most of these will reset themselves after either one night, or a full 24-hour period.

It may be possible that the right connection sequence was not followed. If the site cannot be visited the next day to confirm self-resetting, some controllers can be manually reset by disconnecting and reconnecting the unit. Consult the manufacturer's information for details.

Characteristics of specific charge controllers

Chapter 2 has a list of the general characteristics of charge controllers. For specific installation information, refer to the manufacturer's instructions. If these are not available, contact the manufacturer. Specific information on charge controllers available as of December 1991 are in Appendix E.

If installation information cannot be furnished, consider replacing the controller with one for which this information is available. If the connection sequence is known, write it on a label or tag and attach it to the controller.

5.1.8 Inverters. Generally, inverter failure requires the replacement of the entire unit. Some manufacturers allow the replacement of circuit boards or other components, but these are the exception. Consult the manufacturer for details on repair procedures. Otherwise, replace the unit.

If the inverter has corroded or broken connections, a blown fuse, or a tripped circuit breaker, simple repairs will bring an inverter back to life.

Inverter problems caused by battery voltages which are too high or too low either involve the charge controller itself, charge controller settings, or the relative sizes of the array, the battery bank, and the load. Troubleshoot and repair these problems.

Corrosion or arcing damage of relay contacts usually requires replacement of the relay or the entire inverter. However, if insects or other foreign matter are in the contacts, they can usually be cleaned out without damage to the contacts.

CAUTION!

Do not attempt to file the contact points of relays. Even the use of a "points" file will distort the contact shape, causing a final failure in a short time.

Inverters equipped with a standby feature may be kept on at all times by a small "invisible" load such as a clock or small transformer. If this load must be operated by the inverter output, there is no remedy. Try to find a way to eliminate or replace such loads with ones which do not deplete the battery charge by keeping the inverter on.

If small but essential loads are not turning on inverters with a standby feature, it may be possible to adjust the inverter to increase its sensitivity.

If an inverter must be replaced, be sure the replacement unit has adequate capacity and an appropriate output waveform for the loads. Section 2.5.3 has more information on these subjects.

5.1.9 Loads. Repairs to the loads operated by a photovoltaic system are as important as repairs to other system components.

A major objective is to reduce or limit the energy use of the load, to insure that an adequate reserve of power is always available. For example, keeping the condenser of a photovoltaic-powered refrigerator clean will keep its power consumption from increasing.

Lubricate motors and bearings at recommended intervals. Keep critical components clean. Make sure the loads have adequate ventilation, are in clean environments, and are protected from physical damage.

Additional loads added to the system may hinder performance or cause damage. A classic symptom of this problem is chronically low battery voltage. In this case, either increase the system size or remove some of the loads. In most cases, the number and/or size of loads can be reduced with no impact other than minor inconvenience.

If the polarity of wiring to loads is reversed, correct the polarity error immediately. Even if the load can run this way without damage, you and future service personnel are jeopardized by reversed polarity.

Confirm that all loads:

- have all switches in the correct position,
- have untripped circuit breakers, including thermal circuit breakers, or unblown fuses,
- are plugged in,
- have no internal short circuits,
- are not broken, and,
- are actually being supplied with power.

If loads are not oversized, too numerous, or operating too much of the time, but the voltage at the load is still too low, make sure the wire size to the load is large enough for the length of the wire (Refer to Appendix C).

Replace inadequately-sized wire and/or move the load closer to the photovoltaic system. Either of these options is more cost-effective than adding to the system to overcome wiring deficiencies.

5.2 SAMPLE REPAIR RECORD SHEET

The sample repair record sheet is supplied to record the repairs made to the photovoltaic system. Again, a service log creates a history of the system. Those working on the system in the future will benefit from this information. Repairs made to a system are a critical part of that history.

This historical perspective can be used by future inspectors and troubleshooters to detect patterns of gradual performance decline.

Keep all the system documentation in one place. This can be at the system site, but a better place is in the maintenance shop.

Knowing the system's history can simplify future repairs, and make it possible to combine troubleshooting and repairs on one trip.

SYSTEM REPAIR RECORD SHEET

Site: ______________________________ Date: __________________________

Performed by: ____

Original symptom or complaint: ____

Items inspected or troubleshot, and findings: _________________________________

Items repaired or replaced: ____

System performance after repair/replacement: ______________________________

Notes: ____

____

____

____

____

____

____

____

____

____

____

5.3 QUESTIONS FOR SELF-STUDY

Directions: Choose the best answer to each question.

1) System repairs are most likely to involve which of the following?

   A) Modules
   B) Batteries
   C) Mounting systems
   D) Wiring connections

2) What is a loop of wiring coming into the bottom of an outside junction box called?

   A) A reverse loop
   B) A bonded loop
   C) A drip loop
   D) A bottom loop

3) What is the maximum allowed voltage drop from the service entry to the load?

   A) 2%
   B) 5%
   C) 8%
   D) 11%

4) What color should the insulation on the positive DC conductor be?

   A) Red
   B) White
   C) Any color except green or white
   D) Green

5) Type "T" switches are rated for which applications?

   A) DC
   B) AC
   C) 3-phase
   D) 60 Hz

6) If an exact match cannot be found to replace a module, which of the following should be done?

A) Match the short circuit current
B) Match the open circuit current
C) Match the short circuit voltage
D) Match the open circuit voltage

7) How far down into the earth must grounding rods be driven?

A) Four feet
B) Six feet
C) Eight feet
D) Ten feet

8) What should always be available to neutralize spilled battery acid?

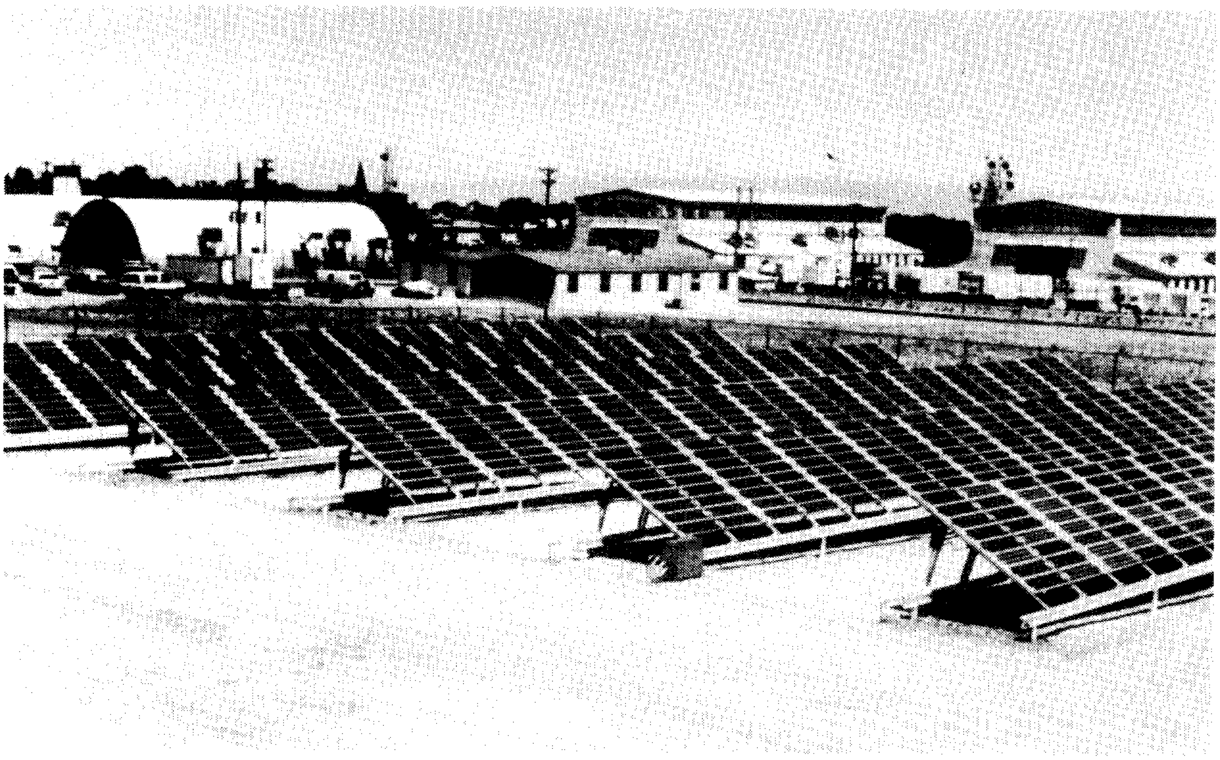
A) Gasoline or kerosene
B) Hydrogen peroxide
C) Ammonia
D) Baking soda

9) The temperature compensation probe of a charge controller should be installed in what location?

A) Outside, exposed to the air and sunlight
B) On the side of one of the batteries
C) In the electrolyte of a cell in the center of the battery bank
D) In the electrolyte of a cell at the edge of the battery bank

10) A charge controller which is out of synchronization can be reset by which of the following?

A) Reversing the array input leads
B) Leaving it alone for 24 hours
C) Removing and reversing its cartridge fuse
D) Replacing the control



40 kW Power System
Yuma Proving Grounds, Arizona

6.0 MAINTENANCE

What You Will Find In This Chapter

This chapter contains information on maintaining a photovoltaic system. It is assumed you understand basic electrical concepts, including those of photovoltaic systems. It is also assumed you can use an electrical meter to measure voltage, current, and resistance.

A great deal of photovoltaic system maintenance is actually inspection. Therefore, information already covered in Chapter 3, Inspection, is not covered in the same depth in this chapter. You will need to refer to Chapter 3 for further information.

Information on normal system operation can be found in Chapter 2, Operation. Information on repairs is provided in Chapter 5, Repair.

Appendix A lists the tools and materials you will need to perform these maintenance operations.

A sample maintenance record sheet is provided at the end of this chapter. Use it to record both the system condition, and any defects found. If repairs cannot be made during this site visit, schedule them for an appropriate time.

The maintenance record sheet does not include a place to record the results of testing the batteries. Make a copy of the battery test section of the inspection record sheet from the end of Chapter 3, Inspection, for this purpose.

6.1 MAINTENANCE PROCEDURES

6.1.1 Permission to Disconnect Critical Loads. Many photovoltaic systems power critical loads, such as communication systems, warning lights, and others. Be sure to get permission from the proper authority to disconnect such loads before doing so. In some cases, an auxiliary power supply may be necessary to operate the load while repairing the photovoltaic system.

WARNING!

Be sure to open disconnect switches during any operation involving wiring. Photovoltaic modules produce electricity whenever they are exposed to light. When working on their wiring, cover them with an opaque material, turn them face down on a clean, soft surface, or work at night.

Battery banks, even at low voltages, can produce potentially lethal amounts of current. Always be careful when working around them.

6.1.2 Scheduling Maintenance. Ideally, these maintenance operations are performed twice a year. The best times are in the spring and fall, before the weather extremes of summer and winter.

If maintenance can only be performed once a year, it should be scheduled for the fall. The system must be brought to top condition before the colder temperatures and reduced sunlight levels of winter place added demands on the system. In addition, some sites may be nearly inaccessible during the winter.

6.1.3 System Meters and Readouts. Leave all system disconnect switches closed (on) for now. Check and record the readings of battery voltage, array current, load current, and any LED's or other system status indicators. Confirm that these readings agree with the status of system components.

For example, if battery voltage is well above the low-voltage disconnect (LVD) setting, but the LVD indicator is on, something is wrong with the charge controller.

6.1.4 Portable Metering. All the disconnect switches should still be closed at this point. With portable electrical meters, refer to Figure 6-1 and measure and record the following readings:

- array voltage at test points D+ and D-,
- battery voltage at test points L+ and L-,
- the current flowing from the array to the batteries at test point M, (or load in a direct system at test points Q and/or S).

Confirm that these readings agree with the status of system components, and are within 10% of the available system meter readings.

Use a voltmeter to check for tripped circuit breakers or blown fuses.

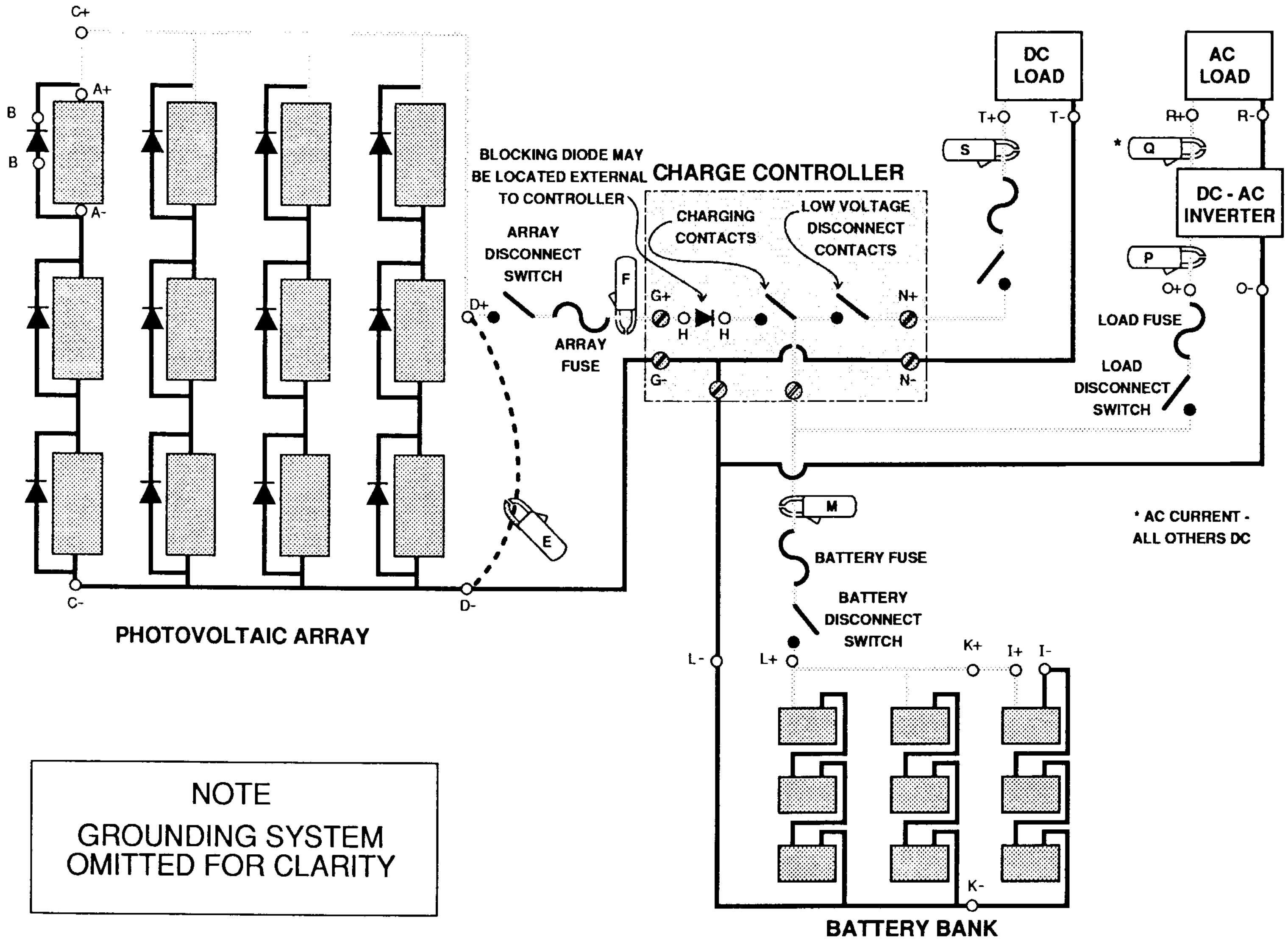


FIGURE 6-1
Photovoltaic System Test Points

FIRST AID INFORMATION

If battery acid should get in your eyes, flush them with water for at least ten minutes and seek immediate medical attention. If acid splashes on your skin, neutralize it immediately with a water and baking soda solution, and flush with plenty of fresh water. If acid is taken internally, drink large quantities of water or milk, follow with milk of magnesia, beaten egg, or vegetable oil, and seek immediate medical attention.

If the tops of the batteries are wet or dirty, remember that fluid on top of the battery is very likely to be highly acidic electrolyte.

Clean the battery top with a cloth or brush and a baking soda and water solution. Rinse with water, and dry with a clean cloth.

Remove the caps from all the cells, and check the electrolyte level of every cell in every battery. If it is not at the manufacturer's recommended level, add distilled water.

The recommended level is usually indicated by a line on the battery. If the batteries have no fill line, and no other information is available, add distilled water until it is one-half inch above the top of the plates.

Replace all the caps, tightening them securely by hand. If flame arrester or recombinant caps are used, they should be on all the cells. Make sure they are all still in good condition.

Repair corroded, loose, or burnt connections. Tighten all wiring connections, and cover them with petroleum jelly or a protective gel or spray made for battery terminals.

Tighten battery tie-downs enough to hold the batteries securely, but not so tight that battery cases are distorted. Repair any corrosion of racks and tie-downs by scraping and repainting with an acid-resistant paint.

If the battery enclosure is locked, make sure the lock and hasp are secure. The enclosure itself should be in good condition and free from corrosion. Make sure any insulation of the enclosure is complete and adequate.

Make sure the batteries are not subjected to temperatures below their freezing points These temperatures are described in Chapter 2, Table 2-3 and 2-4.

Remove any shelves, hooks, or hangers located directly above the batteries.

Make sure the venting system is functional. Clean off holes or louvers in the battery box and make sure they are open for air circulation. If an active venting system with a fan is used, confirm that it is working properly. If the fan motor is a type that requires lubrication, do so, following the manufacturer's recommendations.

If the system site receives snow, make sure the battery enclosure is high enough off the ground so the snow cannot block the vent.

Make sure that a "No Smoking" sign is posted and is highly visible, especially to those entering the area of the batteries.

Equalization charging

An equalization charge is an intentional overcharge of all the battery cells to bring them to an even state of charge. This is necessary because cells with low states of charge will limit the entire battery bank's performance.

WARNING!

Do not perform equalization on parallel strings of batteries. Equalize only series strings of batteries.

Give the battery bank an equalization charge if any of the following conditions exist:

- a new battery has been added to the bank,
- the system is about to be shut down for more than one month,
- the system is starting back up after a shut-down of more than one month, even if it was equalized before shut-down,
- 10% or more of the cells are more than 0.025 below the average specific gravity, or
- 10% or more of the cells are more than 0.1 volts below the average voltage.

To perform an equalization charge, remove the charge controller from the array-battery circuit. Install a blocking diode, of adequate voltage and current capacity, in place of the controller. Disconnect or turn off all the photovoltaic-powered loads.

WARNING!

During charge equalization, provide adequate ventilation for the battery bank. Large amounts of explosive hydrogen gas are generated during the process. Remove all cell caps to allow the gas to escape safely. Wear proper eye and skin protection, have baking soda and water available for acid neutralization, and do not smoke or use fire or spark sources near batteries.

Allow the batteries to charge until the electrolyte in all the cells starts bubbling. It may be necessary to remove some of the batteries from the system in order to get enough current from the array. Check the state of charge of the cells until:

- they are fully charged (as indicated by their specific gravity),
- the voltage of each cell is within 0.05 volts of the average voltage, <u>and</u>
- the specific gravity of each cell is within 0.02 of the average, and has been unchanged for at least five hours.

After the equalization charge, replace lost water in the cells, using distilled water. Replace the cell caps. Remove the blocking diode added for equalization charging. Reconnect the charge controller, following the manufacturer's connection sequence.

Determine the batteries' state of charge. The four ways to do this are described in detail in Section 3.1.7. The most accurate method is to use a hydrometer to measure the specific gravity of the electrolyte in each cell.

Measure and record the state of charge of every cell in every battery. Record this information in a copy of the inspection worksheet supplied at the end of Chapter 3, Inspection.

It is not possible to measure the specific gravity of the cells of sealed batteries. Use the manufacturer's information to determine state of charge from voltage or pressure.

After charge equalization, if the specific gravity of an individual cell is more than 0.025 above or below the average, or its voltage is 0.1 volts higher or lower than the average, the battery must be replaced. Follow all applicable standards and procedures for proper battery disposal.

Seal up the battery enclosure. If it is equipped with a lock, lock it up.

6.1.8 Arrays. Check the modules' glass covers and frames for any damage. Make a note on the maintenance worksheet of any that are broken. Either replace them at this time, or schedule replacement. In most areas, it is a good idea to wash the modules at least once a year. Use a soft cloth, and either plain water or mild dishwashing detergent and water. Be careful not to scratch the glass covers. Do not use brushes, harsh detergents, or any kind of solvent.

If the array includes reflectors, these should also be washed at least once a year. Follow the same procedures.

Repair or replace any bent, corroded, or otherwise damaged mounting components. Check and tighten all mounting system fasteners.

Make seasonal tilt adjustments, if the array is designed for this. If the array tracks the sun, check for proper alignment. This can be done with an object pointing straight out of the module's top surface. A combination square can be used for this purpose (Figure 6-2). If it casts a shadow, the array is not pointed directly at the sun (refer to Section 2.3.5).

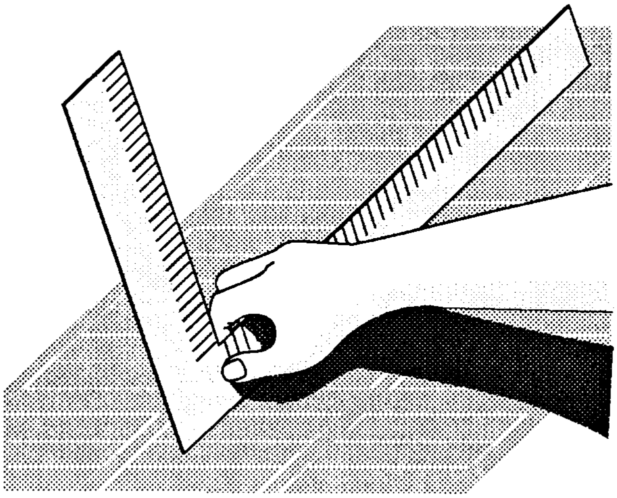


FIGURE 6-2
Using a Combination Square to Check Tracking Array Alignment

Make any necessary adjustments to the array. If the mounting system incorporated theft-resistant features, check these carefully. Report any damage to the appropriate authority, and repair it as soon as possible.

Determine if the array will be shaded during any day of the year. Various solar siting devices are available to show the sun's path across the sky throughout the year (Figure 6-3). Try to remove objects which will cast a shadow on the array.

Repair damaged components in conduit, conduit connectors, and junction boxes. If conduit was not used, check cable insulation carefully.

Remove junction box covers to check wiring and wiring connections for damage or degradation. If repairs are necessary, remember to cover modules, or turn them face down to stop the production of electricity. Also, open disconnect switches to the battery bank.

If plastic conduit is used, check for a continuous grounding wire throughout the system.

FIGURE 6-3
A Solar Siting Device

Photo Courtesy of Solar Pathways, Inc.

Confirm that there are no short circuits or ground faults in the system, as shown in Chapter 3, Figures 3-6 and 3-7.

Measure the open circuit voltage and short circuit current of the array and individual modules. These processes are described in Section 3.1.8.

Remember to multiply the manufacturer's specified current times the number of parallel strings in the array. Multiply the specified voltage times the number of modules in series in each string.

Compare the measured values for the modules against the manufacturer's specifications. If any module is 10% or more below the average voltage or current, note it on the worksheet. Replace these modules, or schedule replacement for as soon as possible.

Try to make these measurements around noon on a clear day. If this is not possible, use an insolation meter to determine how much sunlight is available, as shown in Chapter 3, Figure 3-11. Compare the measured amount of current from the module against the manufacturer's specifications for that amount of sunlight.

6.1.9 Loads. At this time close (turn on) all disconnect switches. Check all loads to be sure they are operating as designed. Perform maintenance operations such as cleaning and lubricating to keep them operating at the highest possible efficiency.

Be sure no new loads have been added that will overload the photovoltaic system. Also make sure that loads designed into the original system are still operating or are being used only for the number of hours per day set up in the original design.

6.1.10 Inverters. Again, remember the impact of the load and the amount of available sun. An oversized load, a load which runs too often, or long stretches of cloudy weather will drain the batteries and reducing system voltage. These will have a negative effect on inverter performance, which may include making it impossible for the inverter to operate at all.

Check the operation of the inverter during maintenance operations. LEDs and meters should agree with inverter operations and the readings of portable meters.

If the inverter has a standby feature, confirm that it will come on when needed by turning on an AC load. Remember that inverters of this type delay for a few seconds when the AC load is first turned on.

Measure and record the current draw of the inverter in both idling and operating states at test point P, and the current draw of the load at test point Q.

If the inverter seems to be delivering too little power for the amount it consumes, check the inverter's measured efficiency against its specified efficiency. Section 2.5.3 has more information on inverter performance.

Check all inverter wiring for loose, broken, corroded, or burnt connections or wires. Look for opportunities for accidental short circuits or ground faults. If not already done, use an ohmmeter to check for these conditions, as described in Section 3.1.8.

The inverter must be in a clean, dry, ventilated, and secure environment. It must never be installed in the battery box. Note and correct any problems.

6.2 MAINTENANCE RECORD SHEET

6.2.1 Procedures. The sample maintenance record sheet is supplied to record the maintenance of a photovoltaic system. Keeping a service log creates a history of the system.

Those working on the system in the future will benefit from this information. They will be able to detect patterns of gradual performance decline.

Keep all the system documentation in one place. This can be at the system site, but a better place is in the maintenance shop. Be sure to bring the information to the site when performing service. Knowing the system's history can simplify troubleshooting, and makes it possible to combine troubleshooting and repairs on one trip, if a problem appears in the future.

Maintenance Check List

Site/Location: ______________________________ Date: ____________

System Meters and Readouts

Battery Voltage: ______ Array Current: ______ Load Current: ______

Charging LED: ☐ On ☐ Off LVD LED: ☐ On ☐ Off

Other LED: ______________ ☐ On ☐ Off

Other LED: ______________ ☐ On ☐ Off

Portable Metering

Array Voltage (test points D+ and D-)

Battery Voltage (test points L+ and L-)

System Current (test point M, P, or S)

- ☐ Circuit breakers not tripped, fuses not blown

Charge Controller

- ☐ Normal operation
- ☐ Wiring connections secure
- ☐ Temperature compensation probe secure and properly located
- ☐ Charge controller properly located and clean

System Wiring

- ☐ Grounding system continuous
- ☐ Disconnect switches operate properly
- ☐ All wiring connections and conduit secure, clean, and uncorroded

Batteries

- ☐ Battery tops clean
- ☐ All cells filled to proper levels
- ☐ Terminal connections secure, clean, protected from corrosion
- ☐ Tie downs and enclosure secure
- ☐ Venting system operating properly
- ☐ Equalization charge performed, if needed
- ☐ Batteries' states of charge recorded on copy of Inspection Record Sheet

Arrays

- ☐ Covers, frames, and reflectors clean and undamaged
- ☐ Seasonal tilt adjustment made, if applicable
- ☐ Tracking checked, if applicable
- ☐ All wiring connections and conduit secure, clean, and uncorroded
- ☐ Open circuit voltage and short circuit current of array and modules measured and recorded on copy of Inspection Record Sheet

Loads

- ☐ All loads operating properly
- ☐ Necessary maintenance and repair operations performed on loads

Inverters

- ☐ Normal operation
- ☐ Wiring connections secure and uncorroded

Current draw in idling mode (test point P):

____

Current draw in operating mode (test point P): ______________________________

Current draw of load (test point Q): ______________________________

Voltage to load (test points R+ and R-): ______________________________

- ☐ Inverter properly located and clean

6.3 QUESTIONS FOR SELF-STUDY

Directions: Choose the best answer to each question.

1) Ideally, maintenance operations are carried out on photovoltaic systems how many times per year?

   A) 12
   B) 6
   C) 4
   D) 2

2) Where should a charge controller's temperature compensation probe be installed?

   A) In the sun, sheltered from the wind
   B) In free air, sheltered from the sun
   C) Between adjacent batteries
   D) Immersed in the battery's electrolyte

3) Where should shunt type charge controllers be installed?

   A) In a clean, ventilated area
   B) In direct sunlight
   C) In the battery enclosure
   D) Anywhere outside

4) What should be used to neutralize battery acid splashed on your skin?

   A) Lemon juice
   B) Baking soda and water
   C) Mineral water
   D) Gasoline or kerosene

5) If batteries have no fill line, to what level should water be added?

   A) The tops of the caps
   B) The tops of the elements
   C) One-half inch below the tops of the plates
   D) One-half inch above the tops of the plates

6) What is an equalization charge?

A) Disconnecting the array to allow all the battery cells to drop to the same voltage
B) Disconnecting the array and load to allow all the battery cells to equalize their voltages
C) Disconnecting the loads to allow all the battery cells to equalize their voltage
D) Disconnecting the loads to allow an intentional overcharge of all the battery cells

7) An equalization charge should be done when 10% or more of the cells in the battery bank are how far below the average specific gravity?

A) 0.015
B) 0.025
C) 0.035
D) 0.045

8) What type of water should be added to batteries?

A) Distilled
B) Softened
C) Mineral
D) Tap

9) Checking tracking array alignment can be done with which tool?

A) A level
B) A compass
C) An inclinometer
D) A square

10) What effect does snow have on a photovoltaic system?

A) It can reduce inverter efficiency
B) It can corrode intercell connections on the modules
C) It can block off battery enclosure vents
D) It can reduce the effectiveness of the grounding system

REFERENCES

References

1. Bower, W., J. Dunlop and C. Maytrott, "Performance of Battery Charge Controllers: An Interim Test Report," Proceedings of 21st IEEE Photovoltaics Specialists Conference - 1990, Kissimmee, Florida, May 21-25, 1990.

2. Vinal, George W., Storage Batteries, Fourth Edition, John Wiley and Sons, 1965.

3. Kiehne, H.A., Battery Technology Handbook, First Edition, Marcel Dekkar, Inc., 1989.

4. Linden, D., Handbook of Batteries and Fuel Cells, McGraw-Hill, 1984.

5. Allen, W.R., et al., "Evaluation of Solar Photovoltaic Energy Storage for Aids to Navigation," CG-D-5-81, United States Coast Guard, NTIS, Springfield, VA, 1981.

6. Harrington, S.R., "Charge Controller Testing Status at SNL as of 6 Months," Sandia National Laboratory (SNL) PV Design Assistance Center, June 1991.

7. Harrington, S.R., "Photovoltaic Powered Stand-Alone Lighting Systems for Southern California Edison Research Center", Sandia National Laboratory, April 1991. Internal Sandia Report - not for distribution.

8. Lane, C., Dunlop, J., and W. Bower, "Cecil Field Photovoltaic Systems Evaluation," Prepared for Sandia National Laboratory, August 1990. Internal Sandia Report - not for distribution.

REFERENCES

9. Hammond, B. and J. Dunlop, "Venice Photovoltaic Systems Evaluation," Prepared for Sandia National Laboratory, July 1991. Internal Sandia Report - not for distribution.

APPENDIX A

Tools, Materials, and Supply Lists

Tool List

Because many photovoltaic systems are in remote locations, this list is made up of tools which generally must be taken to the site. They can be carried in a large backpack, if the site is not accessible by vehicles.

Other tools can be added to this list, particularly if a vehicle can access the site. Battery-powered tools, fully charged, are an example of a tool which performs the same function with less effort than the hand tools listed here. It may be feasible to take an inverter to supply AC power to tools from the system or vehicle batteries.

Some systems will require tools not listed here. For example, a tall array will require a ladder, which must normally be brought to the site with a vehicle. Make notes here, or in the service log of the system, about the unusual tools or materials which are required for a particular system.

Whenever repair or replacement operations are performed, prefabricate as many assemblies as possible. For example, build a new battery enclosure in the shop, not in the field. Even if it must be backpacked to the site in pieces, it will only require final assembly at the site.

TABLE A-1: Recommended Tool List

Tool	Inspection	Troubleshooting	Repair	Maintenance
First Aid Kit	X	X	X	X
Volt-Ohm Meter	X	X	X	X
Snap around (Clamp-on) Ammeter	X	X	X	X
Hydrometer/Refractometer	X	X	X	X
Screwdrivers				
Slotted	X	X	X	X
Phillips	X	X	X	X
Nutdrivers, 1/4in. and 5/16in.	X	X	X	X
25ft. Tape Measure	X	X	X	X
Inclinometer	X	X	X	X
Compass	X	X	X	X
Flashlight	X	X	X	X
System Service Log	X	X	X	X
Manufacturerft.s Literature	X	X	X	X
This O&M Manual	X	X	X	X
Paper/Pencil	X	X	X	X
Insolation Meter	X	X	X	X
Solar Site Analyzer	X	X	X	X
Safety Goggles or Face Shield		X	X	X
Rubber Gloves		X	X	X
Combination Square		X	X	X
Tool Pouches			X	X
Wire Strippers/Crimpers			X	X
Needle nose Pliers			X	X
Linesman Pliers			X	X
Diagonal Cutters			X	X
Soldering Iron, Battery-powered			X	X
Hacksaw			X	X
Battery Terminal:				
Cleaner			X	X
Puller			X	X
Clamp Spreader			X	X

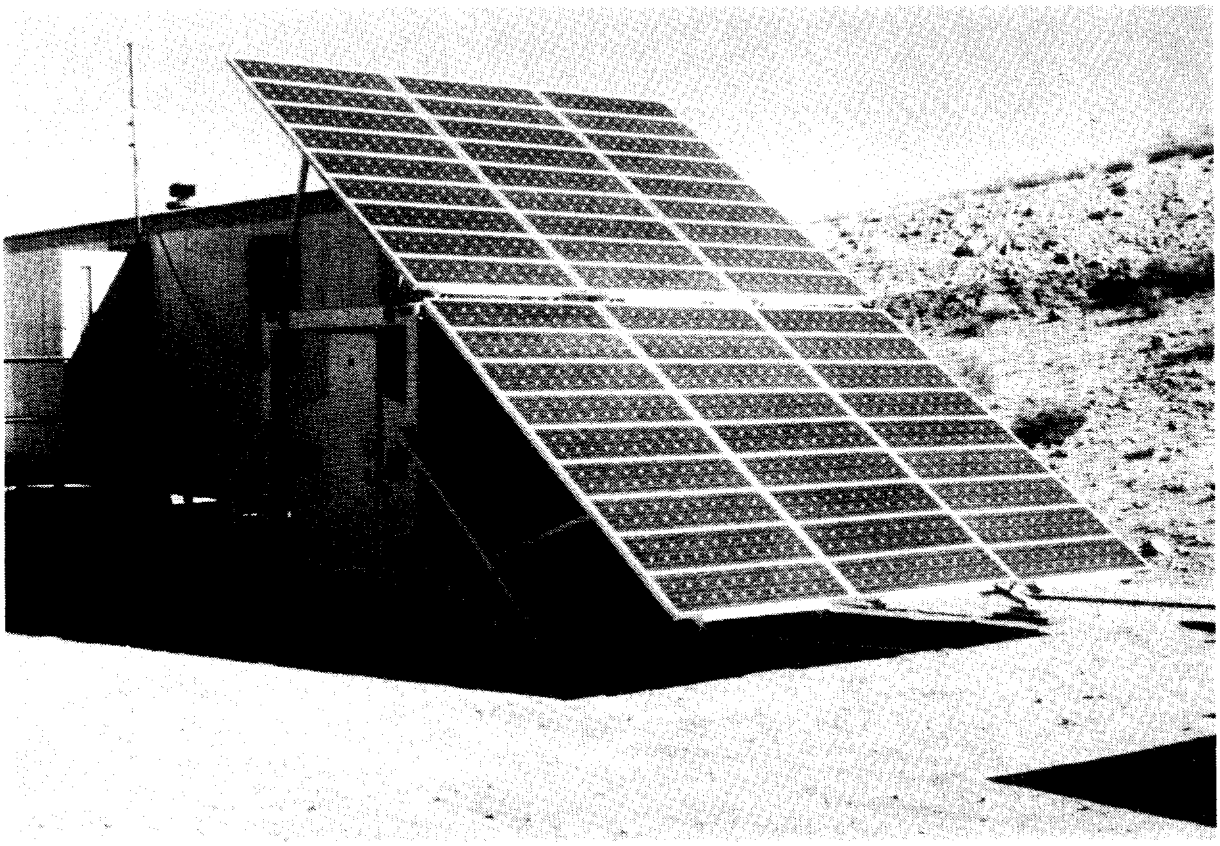
The column headers Inspection, Troubleshooting, Repair and Maintenance are printed under the heading **Needed for:**

TABLE A-1: Recommended Tool List (continued)

Tool	Inspection	Troubleshooting	Repair	Maintenance
Utility Knife			X	X
Hammer			X	X
Cell Water Filler			X	X
Cleaning Brush			X	X
Small Container (to mix baking soda and water in)			X	X
Caulking Gun			X	X

TABLE A-2: Recommended Materials and Supplies List for Repair or Maintenance

- Distilled Water
- Baking Soda
- Wire Nuts
- Crimp Connectors
- Ring, Spade, and Lug Terminals
- Load, Inverter, and Charge Controller Fuses
- Rosin Core Electrical Solder
- Conduit Connectors
- Cable Ties
- Rags or Paper Towels
- Dish Soap or Pulling Grease
- Assorted Fitting Screws
- Red and Black Electrical Tape
- Assorted Screws and Nails
- Mounting Hardware, as needed
- Cable, Wire and/or Conduit, as needed
- Anti-oxidizing Compound
- Silicone Sealant



Portable 2.5 kW System

APPENDIX B

Photovoltaic Suppliers

The following is a list of suppliers to the photovoltaic industry. Inclusion on this list is not an endorsement, nor is this list meant to be comprehensive. These companies market products appropriate for use in stand-alone, small-scale, photovoltaic systems.

A Rich Kretchman
710 Pan Am Avenue
Naples, FL 33963
813-598-3707
Distributor

A.Y McDonald Mfg. Co.
4800 Chavenelle Road
PO Box 508
Dubuque, IA 52004-0508
319-583-7311/800-292-2737
DC pumps, wind generators, and batteries

Abacus Controls, Inc.
PO Box 893
Somerville, NJ 08876-0893
201-526-6010
Inverters and controls

Advanced Energy Construction
505 U.S. Highway 19 South Suite 376
Clearwater, FL 34624
813-449-2509
Distributor

Advanced Photovoltaic Syst Inc.
195 Clarksville Road
Lawrenceville, NJ 08543
609-275-5000
Modules, controls,inverters, production equipment, and engineering services

All Solar Systems
505 S.W. 3rd Street
Hallandale, FL 33009
305-458-5795
Distributor

Alternative Energy Engineering
PO Box 339
Redway, CA 95560
900-777-6609
Distributor

Ample Power Company
1150 N.W. 52nd Street
Seattle, WA 98107
800-541-7789
Amp-hour monitor

Apollo Energy Systems, Inc.
PO Box 238
Navasota, TX 77868
800-535-8488
Pumps

Applied Energy Technology Ltd.
PO Box 588
Barrington, IL 60011
708-381-8833
Distributor

Armech Solar
PO Box 7906
Atlanta, GA 30309
407-740-9955
Modules

AstroPower Inc.
30 Lovett Avenue
Newark, DE 19711
302-366-0400
Cells, modules, PV manufacturing equipment, and complete systems

Atlantic Solar Power
PO Box 70060
Baltimore, MD 21237
301-686-2500
Distributor

Backwoods Cabin Electric Systems
8530 Rapid Lightning Creek Road
Sandpoint, ID 83864
Charge controllers

Basler Electric
P.O. Box 269
Highland,IL 62249
618-654-2341
Charge controllers

Bobier Electronics, Inc.
512 37th Street
PO Box 1545
Parkersburg, WV 26101
304-485-7150
Charge controllers

C&D Batteries
3043 Walton Road
Plymouth Meeting, PA 19462
215-828-9000
Batteries

Chloride Batteries
PO Box 492
North Haven, CT 06473
203-777-0037
Batteries

Climatic-Solar
356 Eugenia Road
Vero Beach, Fl 32963
407-567-3104
Distributor

Commercial Energy Specialists
1530 Cypress Drive
Suite 203
Jupiter, FL 33469
407-744-1557
Distributor

Creative Energies of Palm Beach
1011 6th Avenue South
Lake Worth, FL 33460
407-586-3839
Distributor

Currin Corporation
P.O. Box 1191
Midland, MI 48641-1191
517-835-7387
Charge controllers

Dytek-Charles Marine Products
5600 Apollo Drive
Rolling Meadows, IL 60008
708-806-6300
Inverters

Efficient Homes
321 S.W. 83rd Avenue
N. Lauderdale, FL 33068
305-722-3708
Distributor

ECS
4110 S.W. 34th Street #15
Gainesville, FL 32608
904-373-3220
Distributor

ENTECH, Inc.
PO Box 612246
1015 Royal Lane
DFW Airport, TX 75261
214-456-0900
Modules, complete systems, and engineering services

EPOS-PVI
PO Box 7456
Princeton, NJ 08543-7456
609-452-7456
Lights, pumps, power packs, and custom systems and components

Echo Energy Products
219 Van Ness Avenue
Santa Cruz, CA 95060
408-423-2429
PV support structures

Electron Connection
PO Box 203
Hornbrook, CA 96044
916-475-3401
Distributor

Energy Depot
61 Paul Drive
San Rafael, CA 94903
415-499-1333/800-822-4041
Distributor

Energy Equipment Sales
412 Longfellow Boulevard
Lakeland, FL 33801
813-665-7085
Distributor

Energy Products and Services, Inc.
321 Little Grove Lane
Fort Myers, FL 33917
813-997-7669
Distributor

Energy Specialists
PO Box 188710
Sacramento, CA 95818
916-392-7526
Distributor

Energy Transformers, Ltd.
PO Box 588
St. Vincent, West Indies
809-456-1747
Distributor

Engineered Service Co.
1606 Terrace Street
Cocoa, FL 32922
407-631-9373
Distributor

Exide Corp.
PO Box 14205
Reading, PA 19612
215-674-9500
Batteries

Florida Solar and Energy Systems, Inc.
PO Box 14396
Tampa, FL 33609
813-253-3518
Distributor

GNB, Industrial Battery Divisions
829 Parkview
Lombard, IL 60148
708-629-5200
Batteries

Globe Battery Division
5757 N. Green Bay Avenue
Milwaukee, WI 53212
414-228-1200
Batteries

Grundfos Pumps Corp.
2555 Clovis Avenue
Clovis, CA 93612
209-292-8000
Inverters, submersible pumps, and motors

Heart Interface
811 South 1st Avenue
Kent, WA 98032
206-854-0640
Inverters

Heliotrope General
3733 Kenora Road
Spring Valley, CA 92077
800-552-8838
Controls/regulators and inverters

Hoxan America (Japan)
PO Box 5089
Culver City, CA 90231
213-202-7882
Modules

Integrated Power Corporation
7524 Standish Place
Rockville, MD 20855
301-294-9133
Controls/regulators, inverters, complete systems, and hybrid systems

Jade Mountain
PO Box 4616
Boulder, CO 80306-9846
303-449-6601/800-442-1972
Catalog

Johnson Controls - Battery Group
900 E. Keefe Avenue
Milwaukee, WI 53201
414-228-1200
Batteries

Kopin Corp.
695 Myles Standish Boulevard
Taunton, MA 02780
508-824-6696
Cells

Kyocera America Inc.
8611 Balboa Avenue
San Diego, CA 92123
619-576-2647/800-537-0294
Modules

Laing Thermotech, Inc.
632 Marsat Court
San Diego, CA 92011
619-575-7466
DC and AC pumps

M. Hutton and Company
4112 Billy Mitchell Drive
Dallas, TX 75244
800-442-3811
Distributor

Marisol International Inc.
1011 S. Tamiami Trail
Nokomis, FL 34275
813-484-0130
Distributor

Midway Labs, Inc.
2255 E. 75th Street
Chicago, IL 60649
312-933-2027
Concentrator modules, complete systems, and engineering services

Mobile Solar Energy Corp.
4 Suburban Park Drive
Billerica, MA 01821
508-667-5900
Modules, PV manufacturing equipment, and engineering services

NIFE Inc.
PO Box 7366
251 Industrial Avenue
Greenville, NC 27835
919-830-1600
Batteries

Northern Power Systems
One North Wind Road
PO Box 659
Moretown, VT 05660-0659
802-496-2955
Hybrid systems

Omnion Power Engineering Corp.
188 Highway ES
Mukwonago, WI 53149
414-363-4088
Inverters

Pacific West Supply Company
16643 S.W. Roosevelt
Lake Oswego, OR 97035
503-835-1212
Distributor

Photocomm, Inc. (BOSS)
7681 E. Gray Road
Scottsdale, AZ 85260
800-223-9580
Modules, complete systems, engineering services, and hybrid systems

Photron, Inc.
PO Box 578
77 West Commercial
Willits, CA 95490
707-459-3211
Trackers, batteries, controls, meters, and mounting systems

Polar Products
2808 Oregon Courts, Bldg K-4
Torrance, CA 90503
213-320-3514
Charge controllers

Power Sonic Corp.
PO Box 5242
Redwood City, CA 94063
415-364-5001
Batteries

Power Star Products
1011 North Foothill Boulevard
Cupertino, CA 95014
408-973-8502
Inverters

R.P. Smith Plumbing
607 W. Mowry Street
Homestead, FL 33033
305-246-4599
Distributor

Real Goods
966 Mazzoni Street
Ukiah, CA 95482
800-762-7325
Catalog

Remote Power, Inc.
1608 Riverside Avenue
Fort Collins, CO 80524
303-482-9507
Distributor

Robbins Engineering, Inc.
1641-25 McCulloch Blvd. #294
Lake Havasu City, AZ 86403
602-855-3670
Support structures and trackers

Rocky Mountain Solar Electric
2560 28th Street
Boulder, CO 80301
303-444-5909
Distributor

Segal's Solar Systems
3357 Cranbery Street
Laurel, MD 20707
301-776-8946
Distributor

Sennergetics
8751 Shirley Avenue
Northridge, CA 91324
818-885-0323
Distributor

Siemens Solar Industries
4650 Adohr Lane
PO Box 6032
Camarillo, CA 93010
805-482-6800
Modules and controls

Simpler Solar Systems, Inc.
3118 West Tharpe
Tallahassee, FL 32303
904-576-5271
Distributor

Skyline Engineering
RR1, Box 22OC
Potato Hill Road
Fairlee, VT 05045
802-333-9305
Distributor

Solamerica Corporation
1046 Harper Blvd. S.W.
Palm Bay, FL 32908
407-723-2725
Distributor

Solar Electric
116 4th Street
Santa Rosa, CA 95401
707-542-1990
Distributor

Solar Electric Specialties Company
PO Box 537
Willits, CA 95490
800-344-2003
Distributor

Solar Energy Systems, Inc.
7300 S.W. 112th Street
Miami, FL 33156
305-253-6599
Distributor

Solar Engineering Services
1210 Homann Drive S.E.
Lacey, WA 98503
206-438-2110
Distributor

Solar Heating Systems
13584 49th Street
Clearwater, FL 33520
813-572-3916
Distributor

Solar Kinetics
10635 King William Drive
Dallas, TX 75220
214-556-2376
PV concentrator

Solar Ray
317 Whitehead Street
Key West, FL 33040
Distributor

Solar Service and Supply Inc.
4707 Elmhirst Lane
Suite 205
Beltsville, MD 20814
301-503-5343
Distributor

Solarex Corporation
PO Box 6008
1335 Piccard Drive
Rockville, MD 20850
301-948-0202
Distributor

Solartrope Supply Corporation
739 W. Taft Avenue
Orange, CA 92665
714-637-6226
Distributor

Solec International, Inc.
12533 Chadron Avenue
Hawthorne, CA 90250
213-970-0065
Distributor

Southwest Photovoltaic Systems Company
18802 Bluebird Lane
Tomball, TX 77375
Distributor

Specialty Concepts, Inc.
9025 Eaton Avenue
Suite A
Canoga Park, CA 91304
818-998-5238
Controls/regulators

Springhouse Energy Systems, Inc.
Washington Trust Building
Room 412
Washington, PA 15301
412-225-8685
Distributor

State Energy Consultants, Inc.
PO Box 1891
Longwood, FL 32750
407-260-8186
Distributor

Statpower Technologies Corporation
7012 Lougheed Highway
Burnaby, BC V5A 1W2
CANADA
604-420-1585
Pocket power inverters

SunAmp Power Company
1902 N. Country Club Drive #8
Mesa, AZ 85201
602-833-1550/800-677-6527
DC controls and timers

SunPower Corp.
625 Ellis Street
Mountain View, CA 94043
802-968-3403
Cells and modules

Sunelco
PO Box 1499
Hamilton, MT 59840
800-338-6844
Catalog

Sunnyside Solar
RD4, Box 808
Green River Road
Brattleboro, VT 05301
802-257-1482/800-346-3230
Distributor

Sunshine America Enterprises, Inc.
9822 N.E. 2nd Avenue
Suite 12
Miami Shores, FL 33138
305-759-1786
Distributor

Surrette America
PO Box 249
15 Park Street
Tilton, NH 03276
603-286-7770
Batteries

Texas Instruments Inc.
PO Box 655012
MS 35
Dallas, TX 75265
214-995-0155
Cells and modules

Thin Lite Corp.
530 Constitution Avenue
Camarillo, CA 93012
805-987-5021
Lighting fixtures

Tidelands Signal Corp.
PO Box 52430
Houston, TX 77052
713-681-6101
Modules and batteries

Trace Engineering
5917 195th Street NE
Arlington, WA 98223
206-435-8826
Inverters and charge controllers

Trojan Battery Company
12380 Clark Street
Santa Fe Springs, CA 90670
213-946-8381/800-423-6569
Batteries

Tryon Plumbing and Solar
925 Wagner Place
Fort Pierce, FL 33482
407-465-0284
Distributor

12 Volt Products, Inc.
PO Box 664
Holland, PA 18966
215-355-0525
Distributor

United Marketing Assocaites, Inc.
13620 49th Street North
Clearwater, FL 34622
813-572-6655
Distributor

United Solar Systems Corp.
1100 West Maple Road
Troy, MI 48084
313-362-4170
Amorphous cells, modules, complete systems, and engineering services

Utility Free
PO Box 228
Basalt, CO 81621
303-927-4568
Batteries

Utility Power Group
9410 DeSoto Avenue
Unit G
Chatsworth, CA 91311
818-700-1995
Modules, trackers, inverters, production equipment, and complete systems

Vanner, Inc.
4282 Reynolds Drive
Hilliard, OH 43026-1297
614-771-2718
Inverters

Veritek
P.O. Box 172
Allendale, MI 49401
616-895-5546
Charge controllers

Wattsun Corporation
PO Box 751
Albuquerque, NM 87103
505-242-8024
Trackers

William Lamb Corporation
PO Box 4185
North Hollywood, CA 91607
818-980-6248
Distributor

Zomeworks Corp.
PO Box 25805
Albuquerque, NM 87125
505-242-5354
Distributor

The following are sources of information on general solar and photovoltaic matters. Write or call for information.

Zon Energy Components, Inc.
696 S. Yonge Street
Ormond Beach, FL 32074
904-673-4343
Distributor

American Solar Energy Society
2400 Central Avenue
Suite B-1
Boulder, CO 80301
(303) 443-3130
Conferences and publications

Florida State Energy Center
300 State Road 401
Cape Canaveral, FL 32920
407-783-0300

National Appropriate Technology Assistance Service
U.S. Department of Energy
PO Box 2525
Butte, MT 59702-2525
800-428-2525
Technical information on renewable energy and conservation

Photovoltaic Design Assistance Center
Ron Pate - Division 6223
Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185
505-844-3043
Technical information

Solar Energy Industries Association
777 North Capitol Street N.E.
Suite 805
Washington, DC 20002
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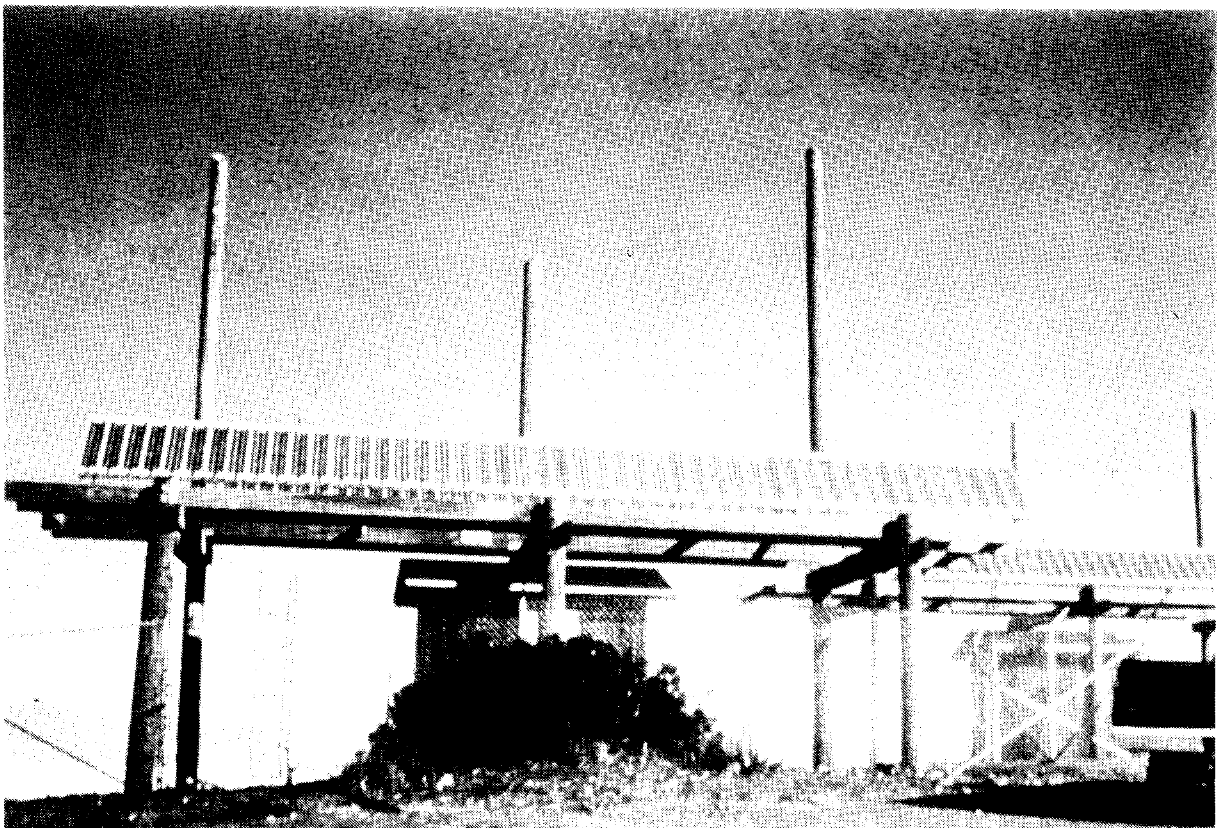


Communication Repeater Station
Camp Pendleton, California

APPENDIX C

Wire Ampacity and Maximum Lengths

Table C-1 lists the maximum number of amps allowed in various gauges of different copper wire types installed in conduit or supplied in cable. Note that these are independent of the length of the conductor. No matter how short the wire is, do not exceed these current ratings. The NEC requires No.12 American Wire Gage (AWG) or larger conductors to be used with systems under 50 volts.

Tables C-2 through C-7 list the maximum one way wire distance for various wire gauge, voltage, and current combinations. The term "one way" means the distance from one connection point to another, not the round trip distance the electricity makes. Put another way, these distances represent the length of the conduit.

> NOTE
>
> Most of the tables in this chapter are for copper wire. Table C-8 lists the maximum ampacities for aluminum wire, and is the only reference to aluminum conductors in this Appendix. Refer to the National Electrical Code, Sections 310-16 to 310-19, for more information on both copper and aluminum wiring and the temperature corrections necessary for operating various types of wires in high ambient temperatures.

TABLE C-1: Maximum Ampacities of Copper Wire in Conduit or Cable

Wire Size, AWG	Dry, Indoor: T, NM, NMC	Wet Indoor or Outdoor: TW	Wet Indoor or Outdoor: THW, THWN	Moist or Underground: UF	Moist or Underground: USE	Battery Cables: THHN
	Acceptable Locations and Wire Type					
14	15	15	15	15	15	15
12	20	20	20	20	20	20
10	30	30	30	30	30	30
8	40	40	50	40	50	55
6	55	55	65	55	65	75
4	70	70	85	70	85	95
3	85	85	100	85	100	110
2	95	95	115	95	115	130
1	110	110	130	110	130	150
1/0	125	125	150	125	150	170
2/0	145	145	175	145	175	195
3/0	165	165	200	165	200	225
4/0	195	195	230	195	230	260

TABLE C-2: Maximum One-Way Copper Wire Distance for 2% Voltage Drop

12 Volt Systems

Amps	Watts	#14	#12	#10	#8	#6	#4	#2	1/0	2/0	3/0
		AWG — Distance in Feet									
1	12	45.0	70.0	115	180	290	456	720	=	=	=
2	24	22.5	35.0	57.5	90.0	145	228	360	580	720	912
4	48	10.0	17.5	27.5	45.0	72.5	114	180	290	360	456
6	72	7.5	2.0	17.5	30.0	47.5	75.0	120	193	243	305
8	96	5.5	8.5	14.5	22.5	35.5	57.0	90.0	145	180	228
10	120	4.5	7.0	11.5	18.0	28.5	45.5	72.5	115	145	183
15	180	3.0	4.5	7.0	12.0	19.0	30.0	48.0	76.5	96.0	122
20	240	2.0	3.5	5.5	9.0	14.5	22.5	36.0	57.5	72.5	91.5
25	300	1.8	2.8	4.5	7.0	11.5	18.0	29.0	46.0	58.0	73.0
30	360	1.5	2.4	3.5	6.0	9.5	15.0	24.0	38.5	48.5	61.0
40	480	-	-	2.8	4.5	7.0	11.5	18.0	29.0	36.0	45.5
50	600	-	-	2.3	3.6	5.5	9.0	14.5	23.0	29.0	36.5
100		-	-	-	-	2.9	4.6	7.2	11.5	14.5	18.3
150		-	-	-	-	-	-	4.8	7.7	9.7	12.2
200		-	-	-	-	-	-	3.6	5.8	7.3	9.2

-Exceeds Ampacity = Over 1,000 Feet Below stepped line - check ampacity

TABLE C-3: Maximum One-Way Copper Wire Distance for 2% Voltage Drop

24 Volt Systems

Amps	Watts	#14	#12	#10	#8	#6	#4	#2	1/0	2/0	3/0
					Distance in Feet						
1	24	90	142	226	360	573	911	=	=	=	=
2	48	45	71	113	180	286	455	724	=	=	=
4	96	22	36	57	90	143	228	362	576	726	915
6	144	15	24	38	60	95	152	241	384	484	610
8	192	11	18	28	45	72	114	181	288	363	458
10	240	9	14	23	36	57	91	145	230	290	366
15	360	6	10	15	24	38	61	97	154	194	244
20	480	-	7	11	18	29	46	72	115	145	183
25	600	-	-	9	14	23	36	58	92	116	146
30	720	-	-	8	12	19	30	48	77	97	122
40	960	-	-	-	9	14	23	36	58	73	92
50	1200	-	-	-	-	11	18	29	46	58	73
100	2400	-	-	-	-	5.7	9.1	14.5	23	29	36.6
150	3600	-	-	-	-	-	-	9.7	15.4	19.4	24.4
200	4800	-	-	-	-	-	-	7.2	11.5	14.5	18.3

-Exceeds Ampacity = Over 1,000 Feet Below stepped line - check ampacity

TABLE C-4: Maximum One-Way Copper Wire Distance for 2% Voltage Drop

120 Volt Systems

Amps	Watts	#14	#12	#10	#8	#6	#4	#2	1/0	2/0	3/0
					Distance in Feet						
1	120	450	700	=	=	=	=	=	=	=	=
2	240	225	350	575	900	=	=	=	=	=	=
4	480	100	175	275	450	725	=	=	=	=	=
6	720	75	120	175	275	450	725	=	=	=	=
8	960	55	85	145	225	355	570	=	=	=	=
10	1,200	45	70	120	190	300	480	765	960	=	=
15	1,800	30	45	70	120	190	300	480	765	960	=
20	2,400	20	35	55	90	145	225	360	575	725	915
25	3,000	18	28	45	70	115	180	290	460	580	730
30	3,600	15	24	35	60	95	150	240	385	485	610
40	4,800	-	-	28	45	70	115	189	290	360	455
50	6,000	-	-	23	36	55	90	145	230	290	365

-Exceeds Ampacity = Over 1,000 Feet Below stepped line - check ampacity

TABLE C-5: Maximum One-Way Copper Wire Distances for 5% Voltage Drop

12 Volt Systems

Amps	Watts	#14	#12	#10	#8	#6	#4	#2	1/0	2/0	3/0
					AWG						
					Distance in Feet						
1	12	113	175	275	450	710	=	=	=	=	=
2	24	56.3	87.5	138	225	355	576	900	=	=	=
4	48	25.0	43.8	68.8	113	178	288	450	725	900	=
6	72	18.8	30.0	43.8	75.0	119	188	300	481	600	760
8	96	13.8	21.3	36.3	56.3	88.8	144	225	363	450	570
10	120	11.3	17.5	28.8	45.0	71.3	113	180	290	360	457
15	180	7.7	11.3	17.5	30.0	47.5	75.0	120	193	240	304
20	240	05.0	08.8	13.8	22.5	36.3	56.3	90.0	145	180	229
25	300	04.5	07.0	11.3	17.5	28.8	45.0	72.5	115	145	183
30	360	03.8	06.0	08.8	15.0	23.8	37.5	60.0	96.3	120	152
40	480	-	-	07.0	11.3	17.5	28.8	45.0	72.5	90.0	114
50	600	-	-	05.8	09.0	13.8	22.8	36.3	57.5	72.5	91.3
100		-	-	-	-	7.2	11.4	18.1	28.8	36.3	45.7
150		-	-	-	-	-	-	12.1	19.2	24.2	30.5
200		-	-	-	-	-	-	9.1	14.4	18.2	22.9

-Exceeds Ampacity = Over 1,000 Feet Below stepped line - check ampacity

TABLE C-6: Maximum One-Way Copper Wire Distances for 5% Voltage Drop

24 Volt Systems

Amps	Watts	#14	#12	#10	#8	#6	#4	#2	1/0	2/0	3/0
					AWG						
					Distance in Feet						
1	24	224	356	566	900	=	=	=	=	=	=
2	48	112	178	283	450	716	=	=	=	=	=
4	96	56	89	142	225	358	569	905	=	=	=
6	144	37	59	94	150	238	379	603	960	=	=
8	192	28	45	71	113	178	285	452	720	908	=
10	240	22	36	57	90	143	228	362	576	726	915
15	360	15	24	38	60	95	152	241	384	484	610
20	480	-	18	28	45	73	113	181	288	363	458
25	600	-	-	23	36	57	91	145	230	290	366
30	720	-	-	19	30	47	75	120	192	242	305
40	960	-	-	-	23	35	57	90	145	182	289
50	1200	-	-	-	-	27	45	73	115	145	183
100	2400	-	-	-	-	14.3	22.8	36.2	57.6	72.6	91.5
150	3600	-	-	-	-	-	-	24.1	38.4	48.4	61.0
200	4800	-	-	-	-	-	-	18.1	28.8	36.3	45.8

-Exceeds Ampacity = Over 1,000 Feet Below stepped line - check ampacity

TABLE C-7: Maximum One-Way Copper Wire Distances for 5% Voltage Drop

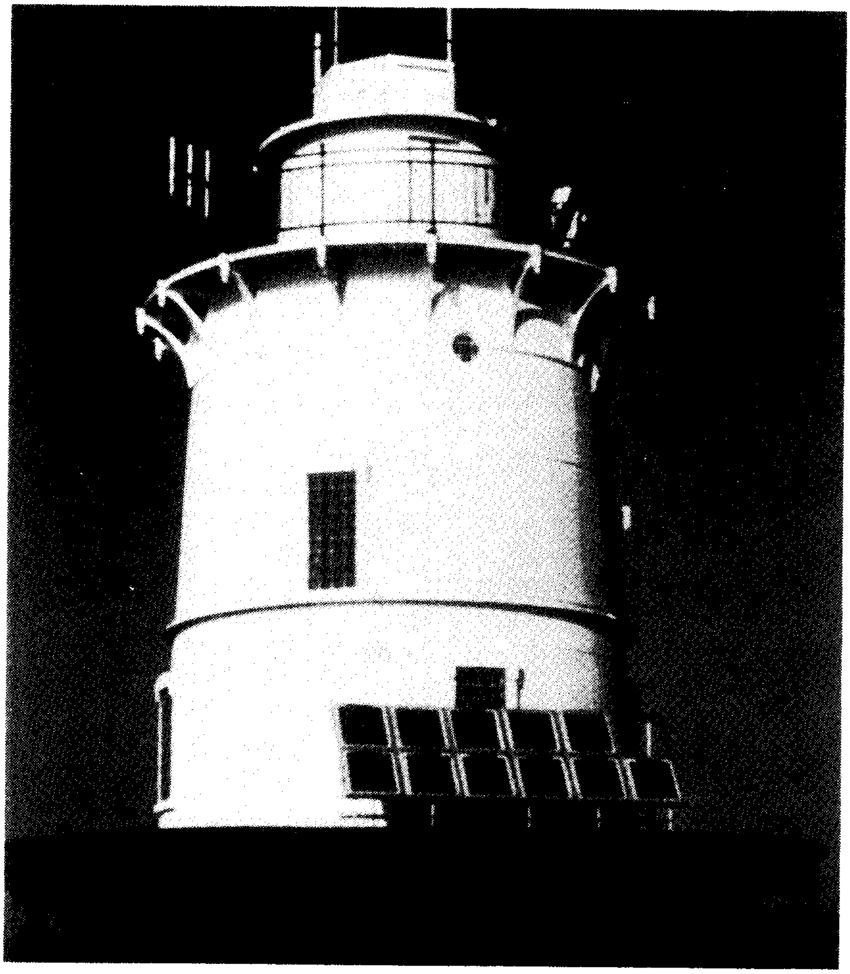
120 Volt Systems

Amps	Watts	AWG #14	#12	#10	#8	#6	#4	#2	1/0	2/0	3/0
		Distance in Feet									
1	120	=	=	=	=	=	=	=	=	=	=
2	240	563	875	=	=	=	=	=	=	=	=
4	480	250	438	688	=	=	=	=	=	=	=
6	720	188	300	438	750	=	=	=	=	=	=
8	960	138	213	363	563	888	=	=	=	=	=
10	1,200	113	175	288	450	713	=	=	=	=	=
15	1,800	75.0	113	175	300	475	750	=	=	=	=
20	2,400	50.0	87.5	138	225	364	563	900	=	=	=
25	3,000	45.0	70.0	113	175	288	450	725	=	=	=
30	3,600	37.5	60.0	87.5	150	238	375	600	963	=	=
40	4,800	-	-	70.0	113	175	288	450	725	900	=
50	6,000	-	-	57.5	90.0	138	228	363	575	725	913

-Exceeds Ampacity = Over 1,000 Feet Below stepped line - check ampacity

TABLE C-8: Maximum Ampacities of Aluminum Wire in Conduit or Cable

Wire Size, AWG	Dry, Indoor: T, NM, NMC	Wet Indoor or Outdoor: TW	Wet Indoor or Outdoor: THW, THWN	Moist or Underground: UF	Moist or Underground: USE	Battery Cables: THHN
	Acceptable Locations and Wire Type					
12	15	15	15	15	15	15
10	25	25	25	25	25	25
8	30	30	40	30	40	45
6	40	40	50	40	50	60
4	55	55	65	55	65	75
3	65	65	75	65	75	85
2	75	75	90	75	90	100
1	85	85	100	85	100	115
1/0	100	100	120	100	120	135
2/0	116	115	135	115	135	150
3/0	130	130	155	130	155	175
4/0	150	150	180	150	180	205



Coast Guard Light House
South Carolina Coast

APPENDIX D

Answers to Questions for Self-Study

Chapter 2

1) B
2) D
3) A
4) A
5) B
6) D
7) D
8) C
9) D
10) C
11) B
12) B
13) D
14) C
15) A

Chapter 3

1) C
2) A
3) A
4) D
5) D
6) B
7) A
8) B
9) C
10) D

Chapter 4

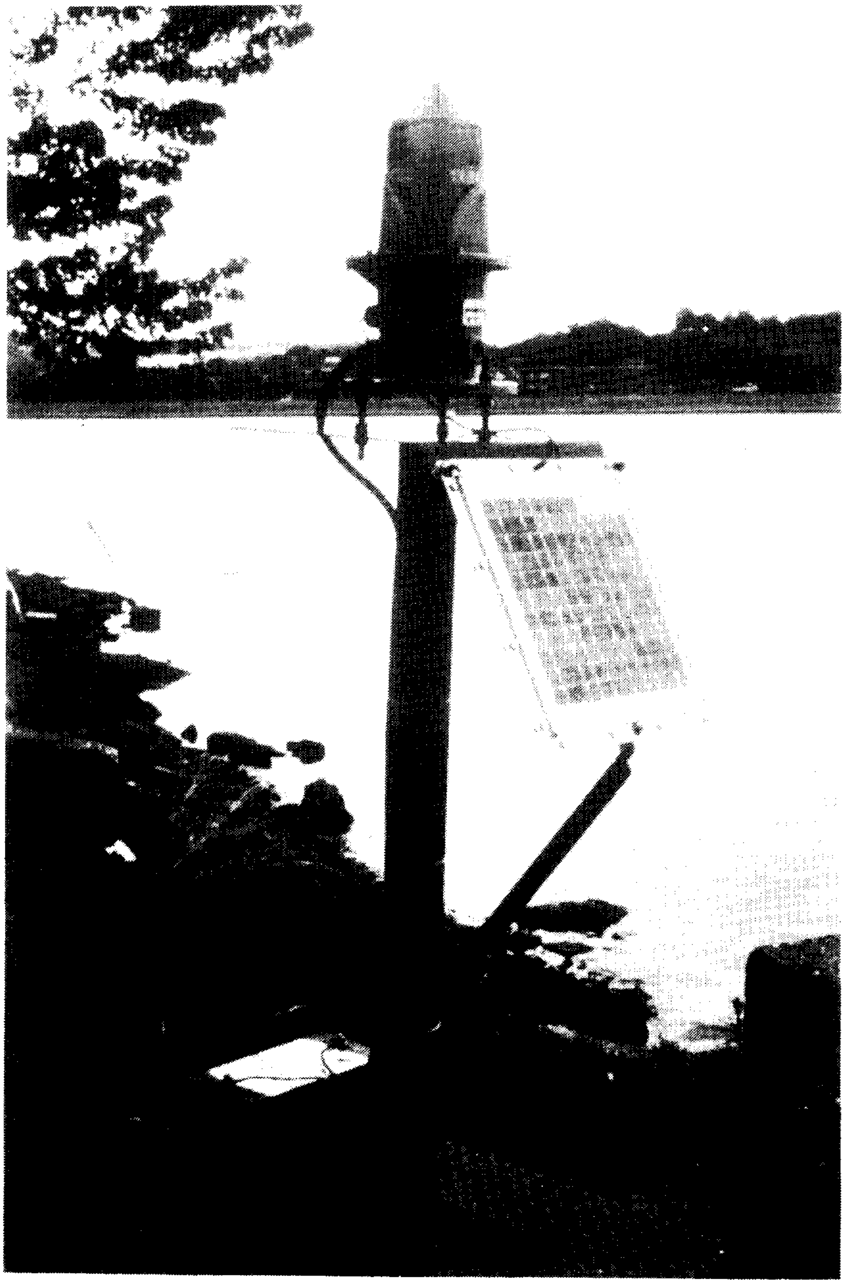
1) D
2) D
3) C
4) B
5) A
6) D
7) A
8) D
9) C
10) A

Chapter 5

1) D
2) C
3) B
4) C
5) A
6) D
7) C
8) D
9) B
10) B

Chapter 6

1) D
2) C
3) A
4) B
5) D
6) D
7) B
8) A
9) D
10) C



Coast Guard Shore Marker

APPENDIX E

Characteristics of Charge Controllers

The following tables summarize the primary specifications of commercially available charge controllers. The tables are organized by manufacturer and present key technical characteristics of each manufacturer's models. The information was provided by each manufacturer through a questionaire prepared by Steve Harrington of Ktech Corporation under the auspices of Sandia National Laboratories Photovoltaic Design Assistance Center. Presentation of this information does not constitute an endorsement of these products or of the accuracy of the data. You are encouraged to obtain specific product specifications directly from the manufacturer. The address of each manufacturer is listed in Appendix B.

Manufacturer & Model Number	Specialty Concepts, Inc. ASC Series	
Charging Algorithm	Shunt Interrupting	
Nominal Voltages Available (VDC)	12	24
Maximum Array Input Voltage (VDC)	22	44
Maximum Charging Current (amps)	Available in 1, 4, 8, 12, and 16 amp	
Battery Voltage (VR) Regulation (VDC)	14.3 ± .2	28.4 ± .4
Battery Voltage Regulation Hysterisis (VRH)	1.1 ± .5	2.2 ± 1.0
VR Temperature Compensation	(optional) -5mv/deg C/cell	
Maximum Load Current (amps)	(optional LVD) 10 amps	
Low Voltage Disconnect (LVD)	11.5 ± .2	23.0 ± .4
Low Voltage Disconnect Hysterisis (LVDH)	1.5 ± .2	3.0 ± .4
LVD Dampened Response (Time Delay LVD)	none	none
Indicators (LED or Meter)	Charging LED, LVD LED	
Standby Current Draw (Milliamperes)	LVD - 30ma Quiescent - 10 ma, Charging - 25 ma	
Operating Temperature Range (°C or °F)	-20°C to +50 °C	
Notes:	Potted in epoxy, suitable for outdoor mounting. MOV lighting protection included. Adjustable VR setting available as an option.	

Manufacturer & Model Number	Specialty Concepts, Inc. SCI Model 1			
Charging Algorithm	Series Interrupting, 2 step, constant current			
Nominal Voltages Available (VDC)	12	24	36	48
Maximum Array Input Voltage (VDC)	22	44	66	88
Maximum Charging Current (Amps)	30,50	30,50	30	30
Battery Voltage (VR) Regulation (VDC)	14.8 ± .2	29.6 ± .4	44.4 ± .6	59.2 ± .8
Battery Voltage Regulation Hysterisis (VRH)	2.3 ± .4	4.6 ± .8	6.9 ± 1.2	9.2 ± 1.6
VR Temperature Compensation	(optional) -5mv/deg C/cell			
Maximum Load Current (Amps)	30 amps	20 amps	15 amps	15 amps
Low Voltage Disconnect (LVD)	11.5 ± .5	23.0 ± 1.0	34.5 ± 1.5	46.0 ± 2.0
Low Voltage Disconnect Hysterisis (LVDH)	1.5 ± .3	3.0 ± .6	4.5 ± .9	6.0 ± 1.2
LVD Dampened Response (Time Delay LVD)	5 - 10 seconds typical			
Indicators (LED or Meter)	Charging LED, LVD LED			
Standby Current Draw (Milliamperes)	10 140	10 100	10 70	10 quiescent 70 LVD
Operating Temperature Range (°C or °F)	-20 °C to +50 °C			
Notes:	*Current compensated load disconnect. Night time array disconnect.* VR adjustable as an option. Reverse polarity protection. MOV lightning protection.			

Manufacturer & Model Number	Specialty Concepts, Inc. PPC			
Charging Algorithm	Series Interrupting, 2 step, constant current			
Nominal Voltages Available (VDC)	12	24	36	48
Maximum Array Input Voltage (VDC)	22	44	66	88
Maximum Charging Current (amps)	30,50	30,50	30	30
Battery Voltage (VR) Regulation (VDC)	14.8 $\pm$ .2	29.6 $\pm$ .4	44.4 $\pm$ .6	59.2 $\pm$ .8
Battery Voltage Regulation Hysterisis (VRH)	2.3 $\pm$ .4	4.6 $\pm$ .8	6.9 $\pm$ 1.2	9.2 $\pm$ 1.6
VR Temperature Compensation	(optional) -5mv/deg C/cell			
Maximum Load Current (amps)	30 amps	20 amps	15 amps	15 amps
Low Voltage Disconnect (LVD)	11.5 $\pm$ .5	23.0 $\pm$ 1.0	34.5 $\pm$ 1.5	46.0 $\pm$ 2.0
Low Voltage Disconnect Hysterisis (LVDH)	1.5 $\pm$ .3	3.0 $\pm$ .6	4.5 $\pm$ .9	6.0 $\pm$ 1.2
LVD Dampened Response (Time Delay LVD)	5 - 10 seconds typical			
Indicators (LED or Meter)	Charge current, battery voltage meters Charging LED, LVD LED			
Standby Current Draw (Milliamperes)	10 140	10 100	10 70	10 quiescent 70 LVD
Operating Temperature Range (°C or °F)	-20 °C to +50 °C			
Notes:	Supplied with enclosure. VR adjustable as an option. Reverse polarity protection. MOV lightning protection.	Current compensated load disconnect. Night time array disconnect.		

Manufacturer & Model Number	Specialty Concepts, Inc. SCI System			
Charging Algorithm	Series Interrupting, 2 step, constant current			
Nominal Voltages Available (VDC)	12	24	36	48
Maximum Array Input Voltage (VDC)	22	44	66	88
Maximum Charging Current (amps)	30,50,90	30,50,90	30,50,90	30,50,90
Battery Voltage (VR) Regulation (VDC)	14.8 ± .2	29.6 ± .4	44.4 ± .6	59.2 ± .8
Battery Voltage Regulation Hysterisis (VRH)	2.3 ± .4	4.6 ± .8	6.9 ± 1.2	9.2 ± 1.6
VR Temperature Compensation	(optional) -5mv/deg C/cell			
Maximum Load Current (amps)	30 amps	20 amps	15 amps	15 amps
Low Voltage Disconnect (LVD)	11.5 ± .5	23.0 ± 1.0	34.5 ± 1.5	46.0 ± 2.0
Low Voltage Disconnect Hysterisis (LVDH)	1.5 ± .3	3.0 ± .6	4.5 ± .9	6.0 ± 1.2
LVD Dampened Response (Time Delay LVD)	5 - 10 seconds typical			
Indicators (LED or Meter)	Digital metering of array, load current, battery volts Charging LED, LVD LED			
Standby Current Draw (Milliamperes)	10 140	10 100	10 70	10 quiescent 70 LVD
Operating Temperature Range (°C or °F)	-20 °C to +50 °C			
Notes:	Supplied with enclosure, load circuit breaker, array fuse. Current compensated load disconnect. MOV lightning protection. VR adjustable as an option. Night time array disconnect. Reverse polarity protection.			

Manufacturer & Model Number	VERITEK PH2-F (for flooded electrolyte battery systems)	VERITEK PH2-G (for gel battery systems)
Charging Algorithm	Series Interrupting, 2 step, constant current	
Nominal Voltages Available (VDC)	12 VDC	12 VDC
Maximum Array Input Voltage (VDC)	32 VDC	32 VDC
Maximum Charging Current (amps)	10 A	10 A
Battery Voltage (VR) Regulation (VDC)	14.2 VDC	14.7 VDC
Battery Voltage Regulation Hysterisis (VRH)	.75 VDC	.75 VDC
VR Temperature Compensation	(optional) probe at -5mV/deg C/cell	
Maximum Load Current (amps)	15 A	15 A
Low Voltage Disconnect (LVD)	10.7 VDC	10.7 VDC
Low Voltage Disconnect Hysterisis (LVDH)	1.0 VDC	1.0 VDC
LVD Dampened Response (Time Delay LVD)	none	none
Indicators (LED or Meter)	LED	LED
Standby Current Draw (Milliamperes)	4 mA	6 mA
Operating Temperature Range (°C or °F)	-20 °C to +50 °C	
Notes:	Available with/without LVD controls.	

Manufacturer & Model Number	Sunamp Power Co PBR Series				
Charging Algorithm	Shunt Interrupting				
Nominal Voltages Available (VDC)	6	12	24	48	Custom
Maximum Array Input Voltage (VDC)	20	24	48	95	2 x Input Voltage
Maximum Charging Current (amps)	6 12	10 20	15 30	18 36	amps Nom. (PU Rating) amps Peak Surge
Battery Voltage (VR) Regulation (VDC)	Set at factory for any battery chemistry including Ni cad.				
Battery Voltage Regulation Hysterisis (VRH)	Set at factory at a nominal 7% of VR setpoint. Can be custom ordered at other values.				
VR Temperature Compensation	Standard, Internal. -5mv/°F/cell				
Maximum Load Current (amps)	NA				
Low Voltage Disconnect (LVD)	NA				
Low Voltage Disconnect Hysterisis (LVDH)	NA				
LVD Dampened Response (Time Delay LVD)	NA				
Indicators (LED or Meter)	LED(s) optional				
Standby Current Draw (Milliamperes)	.003 A + .003 A per LED				
Operating Temperature Range (°C or °F)	-40 °C to +55 °C				
Notes:	All solid state no relays. 1.5 Joule Transient protection. Potted for environmental protection.				

Manufacturer & Model Number	Sunamp Power Co PBRS Series
Charging Algorithm	Shunt Interrupting
Nominal Voltages Available (VDC)	6 12 24 48 Custom
Maximum Array Input Voltage (VDC)	20 24 48 95 2 x Input Voltage
Maximum Charging Current (amps)	4 amps Nom. - 8 amps Peak 8 amps Nom. - 16 amps Peak
Battery Voltage (VR) Regulation (VDC)	Set at factory for any battery chemistry including Ni cad.
Battery Voltage Regulation Hysterisis (VRH)	Set at factory at a nominal 7% of VR setpoint. Can be custom ordered at other values.
VR Temperature Compensation	Standard, Internal. -5mv/°F/cell
Maximum Load Current (amps)	NA
Low Voltage Disconnect (LVD)	NA
Low Voltage Disconnect Hysterisis (LVDH)	NA
LVD Dampened Response (Time Delay LVD)	delay - custom only
Indicators (LED or Meter)	LED(s) optional
Standby Current Draw (Milliamperes)	.003 A + .003 A per LED
Operating Temperature Range (°C or °F)	-40 °C to +55 °C
Notes:	All solid state no relays. 1.5 Joule Transient protection. Epoxy potted for environmental protection.

Manufacturer & Model Number	Sunamp Power Co PBRL Series
Charging Algorithm	Shunt Interrupting
Nominal Voltages Available (VDC)	6 12 24 48 Custom
Maximum Array Input Voltage (VDC)	20 24 48 95 2 x Input Voltage
Maximum Charging Current (amps)	10 15 18 amps Nom. (PU Rating) 20 30 36 amps Peak
Battery Voltage (VR) Regulation (VDC)	Set at factory for any battery chemistry including Ni cad.
Battery Voltage Regulation Hysterisis (VRH)	Set at factory at a nominal 7% of shunt voltage. Can be custom ordered at other values.
VR Temperature Compensation	Standard, Internal. -5mv/°F/cell
Maximum Load Current (amps)	8, 12, 15 amps (nominal) 3 x rating for surge (same as E10)
Low Voltage Disconnect (LVD)	11.7 VDC Nominal, other voltages proportional Factory set as per customer specs.
Low Voltage Disconnect Hysterisis (LVDH)	5% of LVD nominal. Can be set to other values at factory.
LVD Dampened Response (Time Delay LVD)	Delay - available custom only.
Indicators (LED or Meter)	LED(s) optional
Standby Current Draw (Milliamperes)	.003 A + .003 A per LED
Operating Temperature Range (°C or °F)	-40 °C to +55 °C
Notes:	All solid state no relays. 1.5 Joule Transient protection. Potted for environmental protection.

Manufacturer & Model Number	SunAmp Power Co PBRT Series
Charging Algorithm	Shunt Interrupting
Nominal Voltages Available (VDC)	6 12 24 48 Custom
Maximum Array Input Voltage (VDC)	20 24 48 95 2 x Input Voltage
Maximum Charging Current (Amps)	10 15 18 amps Nom. (PU Rating) 20 30 36 amps Peak Surge
Battery Voltage (VR) Regulation (VDC)	Not adjustable. Set at factory for any battery chemistry including Ni cad.
Battery Voltage Regulation Hysterisis (VRH)	Not adjustable. Set at factory for 7% of VR setpoint. Can be custom ordered at other values.
VR Temperature Compensation	Standard, Internal. -5mv/°F/Cell
Maximum Load Current (Amps)	8, 12, 15 Amps (nominal) 3 x rating for surge
Low Voltage Disconnect (LVD)	Not adjustable. 5.85, 11.7, 23.40, 46.80 Can be custom set at factory.
Low Voltage Disconnect Hysterisis (LVDH)	Set at factory for 7% of LVD setpoint. Can be custom set at factory.
LVD Dampened Response (Time Delay LVD)	Optional, custom order.
Indicators (LED or Meter)	LED(s)
Standby Current Draw (Milliamperes)	3 ma + 3 ma/LED
Operating Temperature Range (°C or °F)	-40 °C to +55 °C
Notes:	**Lighting Controller**, sense array current to activate light. "Time On" set by dip switches. All solid state 1.5 Joule Transient protection. Epoxy potted for environmental protection.

Manufacturer & Model Number	Sunamp Power Co PBRE (Extender)
Charging Algorithm	Shunt Interrupting
Nominal Voltages Available (VDC)	6 12 24 48 Custom
Maximum Array Input Voltage (VDC)	20 24 48 95 2 x Input Voltage
Maximum Charging Current (amps)	18 30 36 amps Nom. (PU Rating) 36 60 72 amps Peak
Battery Voltage (VR) Regulation (VDC)	Control from master PBR unit.
Battery Voltage Regulation Hysterisis (VRH)	NA
VR Temperature Compensation	NA
Maximum Load Current (amps)	18, 30, 36 amps (when used as load relay)
Low Voltage Disconnect (LVD)	NA
Low Voltage Disconnect Hysterisis (LVDH)	NA
LVD Dampened Response (Time Delay LVD)	Delay, custom only.
Indicators (LED or Meter)	LED(s) optional.
Standby Current Draw (Milliamperes)	3 ma + 3 ma/ per LED
Operating Temperature Range (°C or °F)	-40 °C to +55 °C
Notes:	All solid state. 1.5 Joule Transient protection. Potted for environmental protection. **Used to extend capability of other PBR series regulators and the SunAmp Master control Board (MCB)**

Manufacturer & Model Number	SunAmp Power Co Master Control Board and Switching Shunts					
Charging Algorithm	Shunt Interrupting					
Nominal Voltages Available (VDC)	6	12	24	48	120	Custom
Maximum Array Input Voltage (VDC)	20	24	48	95	220	2 x
Maximum Charging Current (Amps)	25 to 240 Amps standard, Higher - Custom					
Battery Voltage (VR) Regulation (VDC)	Not adjustable. Set at factory for any battery chemistry including Ni cad.					
Battery Voltage Regulation Hysterisis (VRH)	Not adjustable. Set a factory at a nominal 7% of shunt voltage. Can be custom ordered at other value. Shunt and restore are independently adjustable.					
VR Temperature Compensation	Standard, external - controller near battery area. -30mv/°F for lead acid per 12 V battery.					
Maximum Load Current (Amps)	Any value in 3A, 30A, or 60A increments.					
Low Voltage Disconnect (LVD)	One or two levels independently settable.					
Low Voltage Disconnect Hysterisis (LVDH)	One or two levels independently settable.					
LVD Dampened Response (Time Delay LVD)	Delay, custom only can be set to any value.					
Indicators (LED or Meter)	LED(s) optional, 6 or 9 function DMM optional.					
Standby Current Draw (Milliamperes)	3 ma + 3 ma/LED					
Operating Temperature Range (°C or °F)	-40 °C to +55 °C					
Notes:	All solid state no relays. Air-Core Coils + 1.5 Joule Transient protection. J-Box for environmental protection (any NEMA specs). Other custom features and instrumentation available.					

Manufacturer & Model Number	SunAmp Power Co EMPTB Max Power Tracker
Charging Algorithm	Shunt Interrupting and Series Interrupting (PWM)
Nominal Voltages Available (VDC)	12 24 48 120 Others Custom
Maximum Array Input Voltage (VDC)	120 VDC to 250 VDC depending upon model.
Maximum Charging Current (Amps)	20 A and 40 A, higher on special order.
Battery Voltage (VR) Regulation (VDC)	Set at factory for any battery chemistry including Ni cad. (control comes from PBR unit)
Battery Voltage Regulation Hysterisis (VRH)	Set at factory at a nominal 7% of shunt voltage. Custom values available.
VR Temperature Compensation	Same as PBR's. PV input -.4%/°C. -30mv/°F per 12 V (lead acid).
Maximum Load Current (Amps)	NA
Low Voltage Disconnect (LVD)	Depends on control unit used.
Low Voltage Disconnect Hysterisis (LVDH)	Depends on control unit used.
LVD Dampened Response (Time Delay LVD)	Custom only.
Indicators (LED or Meter)	Optional LED(s) or 4 function DMM.
Standby Current Draw (Milliamperes)	.20 ma varies somewhat with VIN
Operating Temperature Range (°C or °F)	-40 °C to +55 °C
Notes:	Temperature tracks PV cell temperature and uses a DC to DC down converter to maximize battery charging current. High efficiency units available from 200 Wp to 3Kwp of PV input.

Manufacturer & Model Number	Photocomm (Boss) Econocharger	Photocomm (Boss) Solar Sentry
Charging Algorithm	Shunt Interrupting	Shunt Interrupting
Nominal Voltages Available (VDC)	12, 24	12, 24
Maximum Array Input Voltage (VDC)	24, 48	24,48
Maximum Charging Current (Amps)	7	10 & 20 Amp Available
Battery Voltage (VR) Regulation (VDC)	14.45, 28.90 Adjustable potentiometer	
Battery Voltage Regulation Hysterisis (VRH)	.70V, 1.40V	
VR Temperature Compensation	Standard Internal, Optional External Probe -4.5mv/deg C/cell	
Maximum Load Current (Amps)	optional 15 amps	
Low Voltage Disconnect (LVD)	11.50, 23.00 Adjustable potentiometer	
Low Voltage Disconnect Hysterisis (LVDH)	12 V / 24 V	
LVD Dampened Response (Time Delay LVD)	1.5 seconds	
Indicators (LED or Meter)	Optional LEDs Charging, Charged, Discharged	LEDs, Battery Polarity, Panel Polarity Optional: Charging, Charged, Discharged, Battery Disconnect
Standby Current Draw (Milliamperes)	12 V / 24 V	
Operating Temperature Range (°C or °F)	-20 °C to +50 °C	
Notes:	Lighting and transient protection. Epoxy/aluminum housing.	

Manufacturer & Model Number	Photocomm (Boss) Centrix Series				
Charging Algorithm	Series Interrupting				
Nominal Voltages Available (VDC)	12	24	36	48	120
Maximum Array Input Voltage (VDC)	24	48	70	90	230
Maximum Charging Current (Amps)	Available in 60, 100, 200amps				
Battery Voltage (VR) Regulation (VDC)	Adjustable via pot 14.45V	28.90V	43.35V	57.80V	144.50V
Battery Voltage Regulation Hysterisis (VRH)	1.45V	2.90V	4.35V	5.8V	14.50V
VR Temperature Compensation	Standard - external probe, -4.5mv/deg C/cell				
Maximum Load Current (Amps)	Available in 30, 60, and 100 amps				
Low Voltage Disconnect (LVD)	Adjustable via pot 11.50V	23.00V	34.50V	46.00V	115.00V
Low Voltage Disconnect Hysterisis (LVDH)	1.7V	3.4V	5.1V	6.8V	17.0V
LVD Dampened Response (Time Delay LVD)	1.5 seconds				
Indicators (LED or Meter)	LEDs Optional - charged, discharged.				
Standby Current Draw (Milliamperes)	Varies, dependent upon system voltage and load current rating				
Operating Temperature Range (°C or °F)	-20 °C to +50 °C				
Notes:	Standard unit includes: Meters: battery voltage, charge current, transient/lighting protection, Nema 4 enclosure, multiple stage charging, mercury relays, fusing, charge mode control: automatic regulation, array disconnect and continuous charge. Options include blocking diode, generator start contact, alarms (user defined), and array diversion. Custom units available.				

Manufacturer & Model Number	Photocomm (Boss) Power Control Unit	
Charging Algorithm	Series Interrupting	
Nominal Voltages Available (VDC)	12	24
Maximum Array Input Voltage (VDC)	24	48
Maximum Charging Current (Amps)	30 amps	
Battery Voltage (VR) Regulation (VDC)	14.45V	Adjustable via pot 28.90V
Battery Voltage Regulation Hysterisis (VRH)	1.45V	2.90V
VR Temperature Compensation	Standard - external probe, -4.5mv/deg C/cell	
Maximum Load Current (Amps)	30 amps	
Low Voltage Disconnect (LVD)	Adjustable via pot 11.50V	23.00V
Low Voltage Disconnect Hysterisis (LVDH)	1.7V	3.4V
LVD Dampened Response (Time Delay LVD)	1.5 seconds	
Indicators (LED or Meter)	LEDs - charged, discharged.	
Standby Current Draw (Milliamperes)	110 ma	70 ma
Operating Temperature Range (°C or °F)	-20 °C to +50 °C	
Notes:	Standard unit includes: Meters: battery voltage, charge current, load current, array disconnect switch, load circuit breaker, Nema 3R enclosure, transient/lighting protection, Fidd replaceable logic card. Options include: gen start contact, alarms (user defined), array diversion, blocking diode, and Nema 4 enclosure. Custom units available.	

Manufacturer & Model Number	Northern Power Systems SC-PVL
Charging Algorithm	Series Interrupting
Nominal Voltages Available (VDC)	12 VDC 24 VDC 48 VDC 18 VDC 35 VDC 65 VDC
Maximum Array Input Voltage (VDC)	
Maximum Charging Current (Amps)	30 amps at 30 VDC
Battery Voltage (VR) Regulation (VDC)	VR adjustable, dipswitch pV - 2.0 - 2.6 Adjustable volts/per cell
Battery Voltage Regulation Hysterisis (VRH)	Adjustable - separate high/low setpoints.
VR Temperature Compensation	Standard, Probe ± 3 mv / °F / Cell
Maximum Load Current (Amps)	30 amps at 30 volts
Low Voltage Disconnect (LVD)	8.5 VDC, 18 VDC, 40 VDC/ Adjustable, dipswitch
Low Voltage Disconnect Hysterisis (LVDH)	Adjustable w/dipswitch (.04 VPC - .61) Volts per cell.
LVD Dampened Response (Time Delay LVD)	Yes, time delay average voltage sensing (304 min R.C. Network)
Indicators (LED or Meter)	LED Dot Bar Graph
Standby Current Draw (Milliamperes)	3 Watts
Operating Temperature Range (°C or °F)	0 °C to +80 °C standard, other optional
Notes:	

Manufacturer & Model Number	Northern Power Systems SC-351
Charging Algorithm	Series Interrupting , Sub array control
Nominal Voltages Available (VDC)	12 - 120 VDC
Maximum Array Input Voltage (VDC)	
Maximum Charging Current (Amps)	10 Amp - 12 VDC + 24 VDC, 5 Amp - 48 VDC, 2 Amp - 120 VDC
Battery Voltage (VR) Regulation (VDC)	- 4 control setpoints - Screw adjustable
Battery Voltage Regulation Hysterisis (VRH)	Adjustable
VR Temperature Compensation	None
Maximum Load Current (Amps)	10 amps at 24 VDC
Low Voltage Disconnect (LVD)	Adjustable
Low Voltage Disconnect Hysterisis (LVDH)	Adjustable
LVD Dampened Response (Time Delay LVD)	Yes, adjustable, instantaneous - 16 min avg. voltage.
Indicators (LED or Meter)	Ave voltage, output current, instant voltage, control setpoints (LCD display), output voltage.
Standby Current Draw (Milliamperes)	Depends on setup.
Operating Temperature Range (°C or °F)	-35 °C to + 60 °C
Notes:	Negative ground.

Manufacturer & Model Number	Northern Power Systems SC-356/SC-358
Charging Algorithm	Series Interrupting , Sub array control
Nominal Voltages Available (VDC)	12 - 120 VDC
Maximum Array Input Voltage (VDC)	
Maximum Charging Current (Amps)	100 Amp - 12 VDC + 24 VDC, 80 Amp - 48 VDC, 60 amps - 120 VDC
Battery Voltage (VR) Regulation (VDC)	- 4 Control Setpoints - Screw Adjustable
Battery Voltage Regulation Hysterisis (VRH)	Adjustable
VR Temperature Compensation	None
Maximum Load Current (Amps)	100 amps at 24 VDC
Low Voltage Disconnect (LVD)	Adjustable
Low Voltage Disconnect Hysterisis (LVDH)	Adjustable
LVD Dampened Response (Time Delay LVD)	Yes, adjustable, instantaneous - 16 min avg. voltage
Indicators (LED or Meter)	Ave voltage, output current, instant voltage, control setpoints (LCD display), output voltage
Standby Current Draw (Milliamperes)	Depends on setup.
Operating Temperature Range (°C or °F)	-35 °C to + 60 °C
Notes:	Model # 358 - **negative ground only** Model # 356 - **positive or negative ground**

Manufacturer & Model Number	Heliotrope CC-10/CC-20
Charging Algorithm	Series Interrupting , PWM
Nominal Voltages Available (VDC)	12 V
Maximum Array Input Voltage (VDC)	
Maximum Charging Current (Amps)	10/20
Battery Voltage (VR) Regulation (VDC)	13.2 - 15.3 V using dipswitches
Battery Voltage Regulation Hysterisis (VRH)	200 mv - 400 mv
VR Temperature Compensation	Standard and internal to controller.
Maximum Load Current (Amps)	NA
Low Voltage Disconnect (LVD)	NONE
Low Voltage Disconnect Hysterisis (LVDH)	NA
LVD Dampened Response (Time Delay LVD)	NA
Indicators (LED or Meter)	LED's for system status only
Standby Current Draw (Milliamperes)	About 200 ma
Operating Temperature Range (°C or °F)	-15 °C to +50 °C
Notes:	

Manufacturer & Model Number	Heliotrope CC-60/CC-120
Charging Algorithm	Series Interrupting , PWM
Nominal Voltages Available (VDC)	
Maximum Array Input Voltage (VDC)	12 V 12 V
Maximum Charging Current (Amps)	60 (45 w/o fan) / 120
Battery Voltage (VR) Regulation (VDC)	13.5 - 16.5 V 27.0 - 33.0 V Using dipswitches.
Battery Voltage Regulation Hysterisis (VRH)	200 mv - 400 mv
VR Temperature Compensation	Standard and internal to controller.
Maximum Load Current (Amps)	60 (45 w/o fan) / 120
Low Voltage Disconnect (LVD)	Switch adjustable at 10.5 - 11.5 V in 8 steps.
Low Voltage Disconnect Hysterisis (LVDH)	None - time delay.
LVD Dampened Response (Time Delay LVD)	YES
Indicators (LED or Meter)	System status LEDs, digital panel meter.
Standby Current Draw (Milliamperes)	About 200 ma.
Operating Temperature Range (°C or °F)	Up to +200 °F
Notes:	

Manufacturer & Model Number	Polar Products Programmable Charge Controller (PCC)		
Charging Algorithm	Series Interrupting*, sub array control		
Nominal Voltages Available (VDC)	12	24	48 VDC
Maximum Array Input Voltage (VDC)	22	44	88
Maximum Charging Current (Amps)	External relays used, unlimited current.		
Battery Voltage (VR) Regulation (VDC)	3 channels on each PCC allows for multistep charging. 18 turn pot allow hysterisis adjustment from 12 to 16.5 VDC (12 V systems).		
Battery Voltage Regulation Hysterisis (VRH)	Yes. 18 turn pots. Allow up to 4 volt hysterisis adjustment on each channel.		
VR Temperature Compensation	5.14 mv / °C/Cell Standard; on board, variable length extension probe available.		
Maximum Load Current (Amps)	External relay used, unlimited.		
Low Voltage Disconnect (LVD)	Yes, adjustable.		
Low Voltage Disconnect Hysterisis (LVDH)	Yes, 18 turn pots. Allow 4 volt hysterisis adjustment on each channel.		
LVD Dampened Response (Time Delay LVD)	Yes.		
Indicators (LED or Meter)	Three LED.		
Standby Current Draw (Milliamperes)	Logic load 4 ma, w/LED 16 ma		
Operating Temperature Range (°C or °F)	-20 °C to +70°C		
Notes:	* With FTC option: user can adjust current and voltage during float charging (only 12V available, presently). Bipolar transorbs with fuse for lighting/transient protection. Logic board separated from relays for further protection. No on board electrolytics.		

Manufacturer & Model Number	Polar Products Solar Lighting Controller (SLC)
Charging Algorithm	Series Linear, constant voltage
Nominal Voltages Available (VDC)	12 VDC 24 VDC
Maximum Array Input Voltage (VDC)	22 VDC for 12 volt systems, 44 VDC for 24 V systems.
Maximum Charging Current (Amps)	01, 03, 06, 12, 20, 30
Battery Voltage (VR) Regulation (VDC)	Continuous adjustable through 18 turn pot.
Battery Voltage Regulation Hysterisis (VRH)	No hysterisis. Constant voltage (regulated)
VR Temperature Compensation	5.14 mv / °C/Cell Standard; onboard, variable length extension probe available.
Maximum Load Current (Amps)	1 and 3 amp models = 3 amps, 6 to 30 amp models = 12 amps.
Low Voltage Disconnect (LVD)	Yes, range 9.5 - 12 VDC and 19 - 24 VDC adjustable with pot.
Low Voltage Disconnect Hysterisis (LVDH)	Adjustable by changing resistor valve. Approximately 2 volts standard. 1 - 4 volt hysterisis 12 V, 2 - 8 V hysterisis 24 volt.
LVD Dampened Response (Time Delay LVD)	Yes.
Indicators (LED or Meter)	Low voltage disconnected LED.
Standby Current Draw (Milliamperes)	6 ma
Operating Temperature Range (°C or °F)	-20 °C to +70°C
Notes:	Same as SSCC, except: uses PV module for sundown detection, dual timer circuits - one delays turning on load from 0.5 hour to 3.5 hours after sundown. The second timer keeps the light on from 0.5 to 15.5 hours.

Manufacturer & Model Number	Polar Products Small Systems Charge Controller (SSCC)
Charging Algorithm	Series Linear, constant voltage
Nominal Voltages Available (VDC)	12 VDC 24 VDC
Maximum Array Input Voltage (VDC)	22 VDC for 12 volt systems, 44 VDC for 24 V systems.
Maximum Charging Current (Amps)	01, 03, 06, 12, 20, 30
Battery Voltage (VR) Regulation (VDC)	Continuous adjustable through 18 turn pot.
Battery Voltage Regulation Hysterisis (VRH)	No hysterisis. Constant voltage (regulated)
VR Temperature Compensation	5.14 mv / °C/Cell Standard; onboard, or with variable length extension probe.
Maximum Load Current (Amps)	1 and 3 amp models = 3 amps, 6 to 30 amp models = 12 amps.
Low Voltage Disconnect (LVD)	Yes, range 9.5 - 12 VDC and 19 - 24 VDC adjustable with pot.
Low Voltage Disconnect Hysterisis (LVDH)	Adjustable by changing resistor valve. Approximately 2 volts standard. 1 - 4 volt hysterisis 12 V, 2 - 8 V hysterisis 24 volt.
LVD Dampened Response (Time Delay LVD)	Yes.
Indicators (LED or Meter)	Low voltage disconnect LED.
Standby Current Draw (Milliamperes)	6 ma
Operating Temperature Range (°C or °F)	-20 °C to +70°C
Notes: ripple.	MOV across array input, battery input, negative to ground extremely low Conformally coated to MIL - I - 46058C

Manufacturer & Model Number	Solarex Solarstate SSH2/XX/8A		
Charging Algorithm	Shunt Interrupting		
Nominal Voltages Available (VDC)	6	12	24 VDC
Maximum Array Input Voltage (VDC)	12	25	50 VDC
Maximum Charging Current (Amps)	8 A		
Battery Voltage (VR) Regulation (VDC)	2.48 V / Cell at 25°C		
Battery Voltage Regulation Hysterisis (VRH)	~ 0.3 V / Cell		
VR Temperature Compensation	Yes, internal.		
Maximum Load Current (Amps)	NA		
Low Voltage Disconnect (LVD)	NA		
Low Voltage Disconnect Hysterisis (LVDH)	NA		
LVD Dampened Response (Time Delay LVD)	NA		
Indicators (LED or Meter)	LED's		
Standby Current Draw (Milliamperes)	8.7 ma for 12 V		
Operating Temperature Range (°C or °F)	-30 °C to +55°C		
Notes:			

Manufacturer & Model Number	Solarex SHM XX/XXX		
Charging Algorithm	Shunt Linear		
Nominal Voltages Available (VDC)	12	24	36 VDC
Maximum Array Input Voltage (VDC)	25	50	75 VDC
Maximum Charging Current (Amps)	250 watts all voltages.		
Battery Voltage (VR) Regulation (VDC)	2.4 V / 2 V cell at 25°C		
Battery Voltage Regulation Hysterisis (VRH)	Ø V, constant voltage regulated.		
VR Temperature Compensation	Yes, (external probe)		
Maximum Load Current (Amps)	NA		
Low Voltage Disconnect (LVD)	NA		
Low Voltage Disconnect Hysterisis (LVDH)	NA		
LVD Dampened Response (Time Delay LVD)	NA		
Indicators (LED or Meter)	LED's		
Standby Current Draw (Milliamperes)	10 to 50 ma		
Operating Temperature Range (°C or °F)	-40 °C to +76°C		
Notes:	Designed for marine application with failsafe operation.		

Manufacturer & Model Number	Solarex Modular LVD
Charging Algorithm	NA
Nominal Voltages Available (VDC)	12 24 VDC
Maximum Array Input Voltage (VDC)	17 34 VDC
Maximum Charging Current (Amps)	NA
Battery Voltage (VR) Regulation (VDC)	NA
Battery Voltage Regulation Hysterisis (VRH)	NA
VR Temperature Compensation	NA
Maximum Load Current (Amps)	10 A (Relay)
Low Voltage Disconnect (LVD)	1.85 V / 2 V Cell
Low Voltage Disconnect Hysterisis (LVDH)	0.15 V / 2 V Cell
LVD Dampened Response (Time Delay LVD)	NO
Indicators (LED or Meter)	NO
Standby Current Draw (Milliamperes)	~ 1.5 ma
Operating Temperature Range (°C or °F)	-20 °C to +60°C
Notes:	Used with SSH, SHM's when applicable. **Low voltage disconnect unit.**

Manufacturer & Model Number	Solarex SRO XX/XXX	
Charging Algorithm	Series Interrupting	
Nominal Voltages Available (VDC)	12	24 VDC
Maximum Array Input Voltage (VDC)	24	48 VDC
Maximum Charging Current (Amps)	250 watts (all voltages)	
Battery Voltage (VR) Regulation (VDC)	2.4 V / Cell	
Battery Voltage Regulation Hysterisis (VRH)	0.2 V / Cell	
VR Temperature Compensation	Yes, (internal)	
Maximum Load Current (Amps)	10 A (Optional)	
Low Voltage Disconnect (LVD)	1.85 V /Cell	
Low Voltage Disconnect Hysterisis (LVDH)	0.15 V /Cell	
LVD Dampened Response (Time Delay LVD)	NO	
Indicators (LED or Meter)	Optional	
Standby Current Draw (Milliamperes)	10 ma	
Operating Temperature Range (°C or °F)	-40 °C to +60°C	
Notes:		

Manufacturer & Model Number	Solarex SC XX-XXX
Charging Algorithm	Series Interrupting, 2 step dual setpoint
Nominal Voltages Available (VDC)	12 24 36 48 VDC
Maximum Array Input Voltage (VDC)	25 50 75 100 VDC
Maximum Charging Current (Amps)	18 30 60 90, 120 A
Battery Voltage (VR) Regulation (VDC)	(2.5 / 2.35 V)Cell
Battery Voltage Regulation Hysterisis (VRH)	(2.05V / 2.25 V)Cell
VR Temperature Compensation	Yes, (optionally external)
Maximum Load Current (Amps)	10 - 30 A
Low Voltage Disconnect (LVD)	Adjustable
Low Voltage Disconnect Hysterisis (LVDH)	Adjustable
LVD Dampened Response (Time Delay LVD)	NO
Indicators (LED or Meter)	LED, Meters (optional)
Standby Current Draw (Milliamperes)	4 to 50 mA
Operating Temperature Range (°C or °F)	0 °C to +50°C
Notes:	Many options available. Includes VR adjustable, VRH adjustable.

Manufacturer & Model Number	Solarex ACR II XXA/XXV/XXA
Charging Algorithm	Series Interrupting, with a limited 2 step constant current
Nominal Voltages Available (VDC)	6 12 24 48 VDC
Maximum Array Input Voltage (VDC)	12 24 48 96 VDC
Maximum Charging Current (Amps)	30, 90 A
Battery Voltage (VR) Regulation (VDC)	2.4 V / Cell at 25°C
Battery Voltage Regulation Hysterisis (VRH)	0.2 V / Cell
VR Temperature Compensation	Yes, (optionally external)
Maximum Load Current (Amps)	10 - 25 A
Low Voltage Disconnect (LVD)	1.85 V / Cell
Low Voltage Disconnect Hysterisis (LVDH)	0.15 V / Cell
LVD Dampened Response (Time Delay LVD)	No
Indicators (LED or Meter)	LED's and optional meters (current shunts included).
Standby Current Draw (Milliamperes)	40, 25, 20, 60 ma
Operating Temperature Range (°C or °F)	-26 °C to +60°C
Notes:	Many options - VR, ADJ, LVD ADJ. Positive or negative to ground.

Manufacturer & Model Number	Solarex ACR IV ND/XX/NX
Charging Algorithm	Series Interrupting, staged with constant current
Nominal Voltages Available (VDC)	12 24 48 VDC
Maximum Array Input Voltage (VDC)	24 48 96 VDC
Maximum Charging Current (Amps)	210 A
Battery Voltage (VR) Regulation (VDC)	2.40 V / 2.42 V / Cell
Battery Voltage Regulation Hysterisis (VRH)	0.25 V/ 0.27 V / Cell
VR Temperature Compensation	Optional
Maximum Load Current (Amps)	35 A
Low Voltage Disconnect (LVD)	1.85 V / Cell
Low Voltage Disconnect Hysterisis (LVDH)	0.2 V / Cell
LVD Dampened Response (Time Delay LVD)	No
Indicators (LED or Meter)	LED's and meters.
Standby Current Draw (Milliamperes)	130 mA
Operating Temperature Range (°C or °F)	-40 °C to +60°C
Notes:	Higher voltages available. Higher input/output currents available. VR adjustable and LVD adjustable, generator start. **Positive or negative ground.**

Manufacturer & Model Number	Currin Corporation SHCC-3	Currin Corporation ZCCS-1
Charging Algorithm	Shunt Interrupting	Shunt Linear
Nominal Voltages Available (VDC)	For 12 Vdc systems	
Maximum Array Input Voltage (VDC)	30 Vdc	15.5 Vdc (loaded)
Maximum Charging Current (Amps)	3.0 A continuous	1.1 A continuous
Battery Voltage (VR) Regulation (VDC)	14.1 Vdc	14.4 - 15.2 Vdc
Battery Voltage Regulation Hysterisis (VRH)	0.4 Vdc	None
VR Temperature Compensation	-25 mV/°C	None (+6 mV/°C for Zener Diode)
Maximum Load Current (Amps)	•	•
Low Voltage Disconnect (LVD)	None	None
Low Voltage Disconnect Hysterisis (LVDH)	•	•
LVD Dampened Response (Time Delay LVD)	•	•
Indicators (LED or Meter)	None	External LED for low charge warning
Standby Current Draw (Milliamperes)	1.4 mA	1.5 mA (V_{bat} = 13.0 V)
Operating Temperature Range (°C or °F)	-20 °C to +50 °C	+15 °Cto +35 °C
Notes:	Both charge controllers have polarity/voltage indicator to assure correct circuit polarity prior to connections. Both controllers have silicone conformal coating for environmental protection. • No load circuit in controller.	

Manufacturer & Model Number	Bobier Electronics Sunselector M-2, M-4
Charging Algorithm	Shunt Interrupting
Nominal Voltages Available (VDC)	6 12 24
Maximum Array Input Voltage (VDC)	30 30 60
Maximum Charging Current (Amps)	4A (m-2), 7A (m-4)
Battery Voltage (VR) Regulation (VDC)	7.14 14.35 28.7 Flooded electrolyte 7.07 14.15 28.3 Gel electrolyte
Battery Voltage Regulation Hysterisis (VRH)	Ø V 10 seconds PV disconnect
VR Temperature Compensation	Optional, external probe -5mv / deg C / Cell
Maximum Load Current (Amps)	NA
Low Voltage Disconnect (LVD)	NA
Low Voltage Disconnect Hysterisis (LVDH)	NA
LVD Dampened Response (Time Delay LVD)	NA
Indicators (LED or Meter)	Optional charge LED.
Standby Current Draw (Milliamperes)	< 1 ma
Operating Temperature Range (°C or °F)	-40 °C to +65°C
Notes:	Options: Adjustable charge stop, "charge" LED, temp comp, emp protection, and buyer specified setpoints.

Manufacturer & Model Number	Bobier Electronics Sunselector M-8, M-16
Charging Algorithm	Series Interrupting
Nominal Voltages Available (VDC)	6 12 24
Maximum Array Input Voltage (VDC)	15 40 40
Maximum Charging Current (Amps)	10A (m-8), 18A (m-16)
Battery Voltage (VR) Regulation (VDC)	7.14 14.35 28.7 Flooded electrolyte 7.07 14.15 28.3 Gel electrolyte
Battery Voltage Regulation Hysterisis (VRH)	.3 V + 10 sec delay. CKT open ~ 10 sec upon reaching VR or until VRH is reached
VR Temperature Compensation	Optional, external probe -5mv / deg C / Cell
Maximum Load Current (Amps)	NA
Low Voltage Disconnect (LVD)	NA
Low Voltage Disconnect Hysterisis (LVDH)	NA
LVD Dampened Response (Time Delay LVD)	NA
Indicators (LED or Meter)	4 LEDs - charging/analyzing/finishing/PV ready
Standby Current Draw (Milliamperes)	1 ma at night
Operating Temperature Range (°C or °F)	-40 °C to +65°C
Notes:	No blocking diode required. Options: Dual output, adj VR, emp protection, temp comp, and buyer specified setpoints

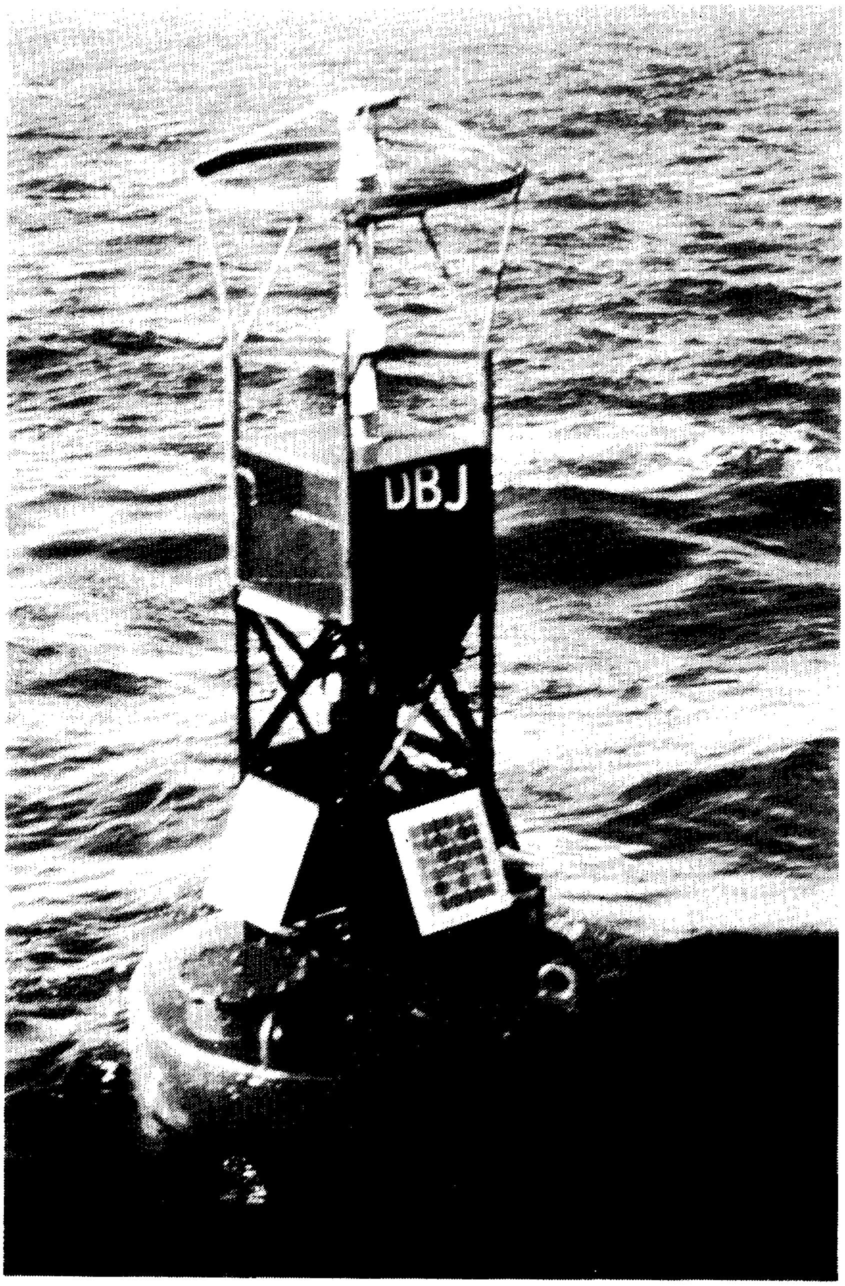
Manufacturer & Model Number	Bobier Electronics LCB 3M, LCB 7M, LCB 20M, LCB 20
Description	Linear Current Booster Optimize power between PV and load.
Nominal Voltages Available (VDC)	8 - 32
Maximum Array Input Voltage (VDC)	50
Maximum Load Current (Amps)	4A (3m), 8A (7m), 40A (20m), 40A (20)
Load Surge Capability	12A (3m), 16A (7m), 80A (20m), 80A (20)
User Adjustments	Available preset at 14.5 or 29.0 VDC. Field adjustment 8 - 32 VDC.
Options	Heavy duty - improved efficiency. - Surge voltages to 100 VDC. Remote control - standard LCB 20 and 20m (ON/OFF) - optional LCB and 7 m
Low Voltage Disconnect (LVD)	
Low Voltage Disconnect Hysterisis (LVDH)	
LVD Dampened Response (Time Delay LVD)	
Indicators (LED or Meter)	
Standby Current Draw (Milliamperes)	< 5 ma
Operating Temperature Range (°C or °F)	No rated lower range, to 80°C.
Notes:	**LCB 20 can be user in battery charging with BCM-1 unit.**

Manufacturer & Model Number	Photron UPC1
Charging Algorithm	User Selectable Series or Shunt Interrupting or Multi-stage Charging
Nominal Voltages Available (VDC)	12 - 120 V
Maximum Array Input Voltage (VDC)	300 V
Maximum Charging Current (Amps)	Unlimited - user selects switch hardware.
Battery Voltage (VR) Regulation (VDC)	Adjustable 0 - 5 V / Cell
Battery * Voltage Regulation Hysterisis (VRH)	* Adjustable 0 - 5 V / Cell - independent of VR
VR Temperature Compensation	Standard external probe. - 30 to 60°C 8 mv/ cell at -30°, 5 mv/ cell at 25°, 2.5 mv/ cell at 60°
Maximum Load Current (Amps)	User selects the switch hardware.
Low Voltage Disconnect (LVD)	Adjustable 0 - 5 V / Cell
Low Voltage Disconnect Hysterisis (LVDH)	Adjustable 0 - 5 V / Cell
LVD Dampened Response (Time Delay LVD)	Yes, selectable on unit. 12 sec to 120s.
Indicators (LED or Meter)	1 LED for each control setpoint. "SA1000" digital meter optional.
Standby Current Draw (Milliamperes)	4 ma
Operating Temperature Range (°C or °F)	-30 °C to +60 °C, -40 °C to +85 °C optional.
Notes:	Many options, call manufacturer.

Manufacturer & Model Number	Photron UPC2
Charging Algorithm	User selectable Series or Shunt Interrupting or Multi-stage Charging or Dual Setpoint
Nominal Voltages Available (VDC)	12 - 240 V
Maximum Array Input Voltage (VDC)	500 V
Maximum Charging Current (Amps)	Unlimited - user selects switch hardware
Battery Voltage (VR) Regulation (VDC)	Adjustable 0 - 5 V / Cell
Battery Voltage Regulation Hysterisis (VRH)	Adjustable 0 - 5V / Cell - independent of VR.
VR Temperature Compensation	Standard external probe – -30 to 60°C. 8 mv/ cell at -30°, 5 mv/ cell at 25°, 2.5 mv/ cell at 60°
Maximum Load Current (Amps)	User selects the switch hardware.
Low Voltage Disconnect (LVD)	Adjustable 0 - 5 V / Cell - independent of VR.
Low Voltage Disconnect Hysterisis (LVDH)	Adjustable 0 - 5 V / Cell - independent of LVD.
LVD Dampened Response (Time Delay LVD)	Yes, selectable on unit. 1 sec standard - adj to 300 sec option.
Indicators (LED or Meter)	1 LED for each control setpoint and 2 LEDs (control inputs). "SA1000" digital meter optional.
Standby Current Draw (Milliamperes)	6 ma
Operating Temperature Range (°C or °F)	-30 °C to +60 °C, -40 °C to +85 °C optional.
Notes:	Can input 2 control signals for controller action.

Manufacturer & Model Number	Photron UPC6
Charging Algorithm	User selectable Series or Shunt Interrupting or Multi-stage Charging or Dual Setpoint
Nominal Voltages Available (VDC)	12 - 240 V
Maximum Array Input Voltage (VDC)	500 V
Maximum Charging Current (Amps)	Unlimited - user selects switch hardware.
Battery Voltage (VR) Regulation (VDC)	Adjustable 0 - 5 V / Cell
Battery Voltage Regulation Hysterisis (VRH)	Adjustable 0 - 5V / Cell - independent of VR.
VR Temperature Compensation	Standard external probe – -30 to 60°C. 8 mv/per cell at -30°, 5 mv/cell at 25°, 2.5 mv/ cell at 60 °C
Maximum Load Current (Amps)	User selects the switch hardware.
Low Voltage Disconnect (LVD)	Adjustable 0 - 5 V / per Cell
Low Voltage Disconnect Hysterisis (LVDH)	Adjustable 0 - 5 V / Cell - independent of LVD.
LVD Dampened Response (Time Delay LVD)	Yes, selectable on unit. 1 sec standard - adj to 300 sec option.
Indicators (LED or Meter)	1 LED for each control setpoint and 2 LEDs (control inputs). "SA1000" digital meter optional.
Standby Current Draw (Milliamperes)	6 ma
Operating Temperature Range (°C or °F)	-30 °C to +60 °C, -40 °C to +85 °C optional.
Notes:	**Usable in positive and/or negative ground systems.** Can input 2 control signal for control action.

Manufacturer & Model Number	Trace C30-A Charge Controller
Charging Algorithm	Series Interrupting , mechanical relay switch
Nominal Voltages Available (VDC)	12 and 24 VDC
Maximum Array Input Voltage (VDC)	56 VDC, over voltage protected with Transorb.
Maximum Charging Current (Amps)	30 amps, fused
Battery Voltage (VR) Regulation (VDC)	VR Adjustable 3.2 to 1.6 VDC / Cell
Battery Voltage Regulation Hysterisis (VRH)	Adjustable (independent of VR) 95% of VR up to 1.6 V / Cell
VR Temperature Compensation	None
Maximum Load Current (Amps)	30 A
Low Voltage Disconnect (LVD)	Automatic nighttime disconnect will disconnect under low current conditions.
Low Voltage Disconnect Hysterisis (LVDH)	(1) Begins periodic sampling at $V_{solar} > 10$ VDC and < 1.5 A (2) Switches in when $V_{solar} > V_{battery}$ and $I_{solar} > 1.5$ A (3) Drops out when $V_{solar} < 10$ VDC and $I_{solar} = ØA$
LVD Dampened Response (Time Delay LVD)	Yes, 4 seconds.
Indicators (LED or Meter)	One status LED with 4 states to indicate various charge modes: on, off, slow and fast flashing.
Standby Current Draw (Milliamperes)	about 10 ma
Operating Temperature Range (°C or °F)	-20 °C to +60 °C - operating -35 °C to +90 °C - storage
Notes:	Features: Conformally coated PCB for environmental protection. No blocking diode needed. Equalize switch to manually equalize liquid electrolyte lead acid batteries.



Coast Guard Navigational Aid

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